WHOI-94-20

Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast

Portland, Oregon, Workshop
July 14-16, 1993

CoOP Report Number 4

by

R.L. Smith
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331

K.H. Brink
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

September 1994

WHOI-94-20

Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast

Portland, Oregon Workshop
July 14-16, 1993

R.L. Smith
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331

K.H. Brink
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Coastal Ocean Processes (CoOP) Report Number 4

September 1994

Technical Report

Funding was provided by the National Science Foundation
under Grant No. OCE92-24824.

Approved for Distribution:

Philip L. Richardson, Chair
Department of Physical Oceanography

Coastal Ocean Processes (CoOP) Reports

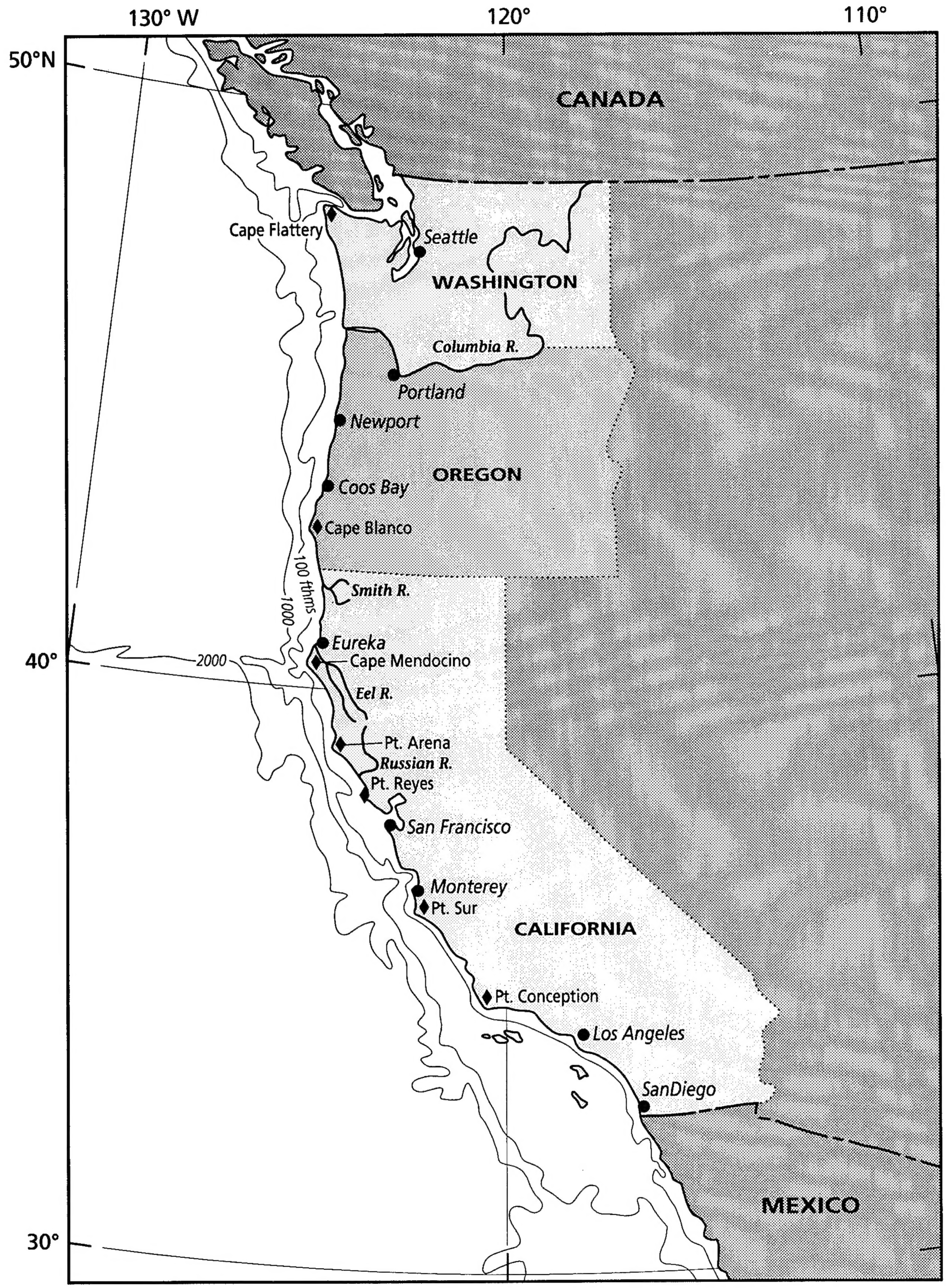
No.

1 *Coastal Ocean Processes (CoOP): Results of an Interdisciplinary Workshop,* 1990, Contribution number 7584 from the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; 51 pp., by K. H. Brink, J. M. Bane, T. M. Church, C. W. Fairall, G. L. Geernaert, D. S. Gorsline, R. T. Guza, D. E. Hammond, G. A. Knauer, C. S. Martens, J. D. Milliman, C. A. Nittrouer, C. H. Peterson, D. P. Rogers, M. R. Roman, and J. A. Yoder.

2 *Coastal Ocean Processes: A Science Prospectus,* 1992, Woods Hole Oceanographic Institution Technical Report, WHOI-92-18, 88 pp., by K. H. Brink, J. M. Bane, T. M. Church, C. W. Fairall, G. L. Geernaert, D. E. Hammond, S. M. Henrichs, C. S. Martens, C. A. Nittrouer, D. P. Rogers, M. R. Roman, J. D. Roughgarden, R. L. Smith, L. D. Wright, and J. A. Yoder.

3 *Long Time Series Measurements in the Coastal Ocean: A Workshop,* 1993, Woods Hole Oceanographic Institution Technical Report, WHOI-93-49, 101 pp., by C. L. Vincent, T. C. Royer and K. H. Brink.

4 *Coastal Ocean Processes: Wind-driven Transport Processes on the U.S. West Coast: Portland, Oregon, Workshop July 14–16, 1993,* 1994, Woods Hole Oceanographic Institution Technical Report, WHOI-94-20, 140 pp., by R. L. Smith and K. H. Brink.



130° W
120°
110°
50°N
40°
30°
CANADA
WASHINGTON
OREGON
CALIFORNIA
MEXICO
Cape Flattery
Seattle
Columbia R.
Portland
Newport
Coos Bay
Cape Blanco
Smith R.
100 fthms
1000
2000
Eureka
Cape Mendocino
Eel R.
Pt. Arena
Russian R.
Pt. Reyes
San Francisco
Monterey
Pt. Sur
Pt. Conception
Los Angeles
SanDiego

Table of Contents

Executive Summary

The overall goal of CoOP (Coastal Ocean Processes) is to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important material on the continental margins. To achieve this overall goal it is necessary to understand the mechanisms, rates, and consequences of cross-margin transport of momentum, energy, solutes, particles, and organisms.

Wind-driven transport occurs on nearly all of the world's continental shelves. The effect of strong alongshore wind in driving the coastal currents and the resulting cross-shelf transport in the surface and bottom boundary layers is of first-order importance in determining the cross-margin transport along the U.S. West Coast, as it is also along the west coasts of South America, Africa, and the Iberian Peninsula. The high biological productivity associated with these regions makes wind-driven systems particularly important from the standpoint of a global scientific understanding of living resources and for economic reasons. The ubiquity of wind forcing on all continental shelves, and the importance of its effects, makes it an appropriate candidate for the first CoOP major interdisciplinary process study.

A workshop, open to all interested scientists, was held in Portland, Oregon, on July 14–16, 1993, to assess the need for a major interdisciplinary study, and to begin defining the relevant questions and approaches. That there are major scientific problems in the coastal ocean off the U.S. west coast still to be addressed, yet ripe for investigation because of advances in observational technology and modeling capabilities, became manifest during the workshop. This is apparent in the interdisciplinary working group reports from the workshop: Bottom Boundary Layer Processes (Appendix 1), Inner Shelf Processes (Appendix 2), Upper Ocean Processes (Appendix 3), Interior Water Column Processes (Appendix 4), and Frontal Processes (Appendix 5). Specific questions were posed in the areas of air–sea feedback, sources and sinks of chemicals in the euphotic zone, plankton distributions and benthic exchanges. The consensus of the entire workshop was that a CoOP study of wind-driven transport processes should be made and should take place over the continental margin adjacent to the U.S. west coast. The central question to be addressed is: What processes control the cross-margin transport of biological, chemical and geological materials in a strongly wind-driven system?

A modern study in the region would follow in the footsteps of the Coastal Upwelling Ecosystem Analysis (CUEA) studies off Oregon in 1972–73, and the Coastal Ocean Dynamics Experiment (CODE) studies off Northern California during 1981–82. Those studies have provided considerable insight on the physics of two phenomena important to wind-driven regions: the locally forced wind-driven offshore transport in the surface boundary layer and the remotely wind-forced coastal trapped waves with several-day periods. Although the CUEA program was interdisciplinary (with a strong biological component), the biological measurements of that era were incommensurate with the physical oceanography component which was utilizing, for the first time in coastal studies, extensive moored time-series measurements of current and temperature, rapid ship-borne profiling of temperature and salinity, and aircraft remote sensing of surface temperature. CODE, which added ship-borne acoustic Doppler current profiling, remote tracking of drifters, and satellite sea surface temperature to the suite of physical measurements, had no biological measurements but did have a strong meteorological component.

In short, the biological and chemical measurements, that are now feasible to make and are needed to answer the most basic questions such as 'What processes control, and maintain, the plankton distributions over the continental margin?' and 'How and where do nutrients, and other chemical species, enter the euphotic zone?' have not been made within studies that adequately measured the physical oceanographic and atmospheric fields. There are also physical measurements, lacking in the previous coastal oceanographic experiments, that are needed to understand and predict the coastal ocean. Most notable are the need for observations in the bottom boundary layer, where there are insufficient measurements to investigate the transport quantitatively, and over the shallow region where the surface and bottom boundary layers are in direct contact (the inner shelf). These are clearly topics of geological interest as well. We also know relatively little about fronts, a common feature in coastal waters, and how frontal processes affect cross-shelf exchange. These topics were emphasized in the physical oceanography discipline report (Appendix 7B) and had sufficient interdisciplinary importance to cause the workshop participants to form the interdisciplinary working groups to address them (Appendices 1–5).

The best locations for field work are determined by the physical setting. The alongshore coastal winds are the dominant forcing from the northwest tip of Washington (48°161′N) to Point Conception (35°161′N) in southern California. During summer, the

alongshore winds are strongly favorable for coastal upwelling but more variable north of about 40°161′N. The difference in the response of the coastal ocean to variable and to persistent wind stress may explain the differences observed in the physical and ecological structure of the coastal ocean in the northern and southern halves of the region. During winter, with the retreat of the North Pacific High southward, low pressure systems from the Gulf of Alaska cause a generally strong northward component in the coastal winds and downwelling along the coast of Oregon and Washington while upwelling generally continues south of San Francisco (37°161′N). Studies of the response of the coastal ocean during downwelling, and of the downwelling process itself, are especially lacking and should be undertaken in a CoOP study of wind-driven processes. Coastal upwelling and downwelling are the ubiquitous responses to surface boundary layer transports forced by local alongshore winds, so these processes have more than regional importance in understanding cross-margin transport. These considerations led the workshop participants to recommend parallel studies north and south of about 40°161′N, with suggested locations being central Oregon and northern California. The logistical ease, the oceanographic background from previous studies, and the relative 'purity' (lack of major riverine, topographic, or tidal effects) of these general regions makes them especially attractive for a CoOP study of wind-driven processes affecting cross-margin transport.

In summary: There was a consensus among the workshop participants on the need for a study of cross-margin transport in a strongly wind-driven domain, and in the opinion that such a study should include both modeling and field studies spanning about two years, off the west coast of the United States.

I. Introduction

Background:

Studies of the coastal ocean have traditionally been made by investigators from one or two disciplines working to understand a specific process or region. This has advanced the understanding of specific processes from the perspective of individual disciplines, and it has brought ocean science to the stage where it can now study important problems that can be addressed only through interdisciplinary studies. The increasing ecological, economical and societal interest in coastal waters has shown the need for scientifically understanding the coastal ocean in its complex totality. With this is mind, an interdisciplinary group of coastal ocean scientists has joined together to form the Coastal Ocean Processes (CoOP) program. The goal, stated in the CoOP Science Prospectus (Brink *et al.*, 1992), is to 'obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins.'

Clearly, understanding cross-margin transport is central to achieving the CoOP goal. Clearly also, the coastal ocean is too geographically diverse to allow a comprehensive region by region approach, so CoOP has decided to 'isolate' important processes having wide applicability and to study them intensively where they are dominant. The CoOP Steering Committee decided that major CoOP process studies be developed with substantial input from the scientific community. The first CoOP workshop to focus on a major process was asked to "create a document that will define a CoOP process study involving cross-margin transport processes centering on the predominantly wind-driven currents of the United States west coast continental shelf and slope." The choice of this topic and region was based on several considerations: (1) the ubiquity of wind-forcing and its effects on the currents and boundary layer transports in coastal waters; (2) the dominance of alongshore winds in forcing cross-margin transport along the U.S. west coast; (3) the shared physical processes and ecological characteristics among several eastern boundary current regions (the west coasts of North and South America, the Iberian peninsula, southwest and northwest Africa) give global significance to a study off the U.S. west coast; (4) the importance to society because of the aesthetic and commercial value of the region affected by these processes; and (5) the synergistic benefits to a CoOP study from spatial and temporal overlap with the major

Global Ocean Ecosystem Dynamics study (GLOBEC) being planned for the California Current region (U.S. GLOBEC Report Number 7, 1992).

The CoOP Scientific Steering Committee sponsored a workshop, "Wind-driven transport processes on the U.S. west coast," which was held at Portland State University in downtown Portland, Oregon, from 14 through 16 July 1993. This report summarizes the discussions at the workshop and presents a science plan based on the reports of the interdisciplinary working groups at the workshop.

The Workshop Goal and Charge:

The goal and charge, as formulated by the CoOP Scientific Committee prior to the workshop, was:

> "to create a document that will define a CoOP process study involving cross-margin transport processes centering on the predominantly wind-driven currents of the United States west coast continental shelf and slope. The planned study must be fully interdisciplinary, and can embrace field work lasting up to about two years, beginning in 1996. The document should address needed modeling, specific choices (and motivations) for geographic locations, and cooperation with other programs, especially GLOBEC. This meeting is intended to be the first of a sequence of CoOP workshops designed to initiate major process studies.
>
> The workshop report must address the following topics:
>
> - What are the important scientific problems to be addressed, and why are they important?
> - How should these problems be addressed in a cohesive, interdisciplinary manner? Answering this question would entail choices about geography for a field study, as well as substantial ideas about modeling and field work. Choices should be rationalized.
> - What are the highest priority questions and approaches?"

The Workshop Structure:

The workshop was open to all interested scientists; an open invitation was widely distributed through bulk mailing and posting on OMNET bulletin boards. The announcement/invitation is given in Appendix 8. About 100 scientists responded to the announcement and about 70 attended (Attendees listed in Appendix 10). This was a good attendance given that, except for an invited speaker and a rapporteur from each of the five disciplines, no specific invitations or reimbursement of expenses were offered. All disciplines were represented, with the majority being physical and biological oceanographers. The agenda/schedule, as realized, is included as Appendix 9 to this report.

The workshop began with the charge to the workshop being discussed. This was followed by a series of invited half-hour talks pointing out the important problems as seen from each of the five disciplinary perspectives; the abstracts of these talks are included in this report (Appendix 6). After this series of 5 talks, the disciplines met separately with their disciplinary speaker and rapporteur to refine and reformulate the problems, keeping the CoOP interest in cross-shelf transport processes in focus and the interdisciplinary imperative in mind. (The attendees were free to choose the discipline discussion group to attend.) The first day finished with all assembling in plenary: The rapporteur of each discipline group was allowed one transparency and 5 minutes to report on the discussions; a general discussion period then followed. The written reports of the discipline group discussions are included as Appendix 7 to this report.

On the evening of the first day, the organizing committee (Smith as chair, Bruland, Dorman substituting for Rogers, Small and Sternberg), the speakers, and the rapporteurs met to define Interdisciplinary Working Groups. In several hours of discussion, it became clear that the interdisciplinary interests and problems could best be discussed by defining Interdisciplinary Working Groups by 'regions:' Bottom Boundary Layer, Inner Shelf, Upper Ocean Processes, Interior, and Frontal Processes.

On the morning of the second day the attendees met in plenary, the Interdisciplinary Working Groups were defined, and the rationale and philosophy were discussed. A rapporteur was assigned to each working group, but the other workshop attendees were free to choose the Working Group of their choice and free to move around. The attendees assembled in plenary at the end of the afternoon to report on their progress and to exchange suggestions. On the final day, the Interdisciplinary Working Groups

chose to continue their group discussions and writing until mid-afternoon, rather than meet in plenary for discussions. Late in the afternoon, the attendees met in plenary and heard 'final' reports from the rapporteurs of each group. There was a striking degree of convergence in terms of questions and approaches among the working groups, but no time remained at the workshop for the workshop attendees to refine and meld the discussions and questions of each group into questions and approaches for a single study. Nonetheless, the ingredients for a science plan were provided by the Interdisciplinary Working Group reports and a single broad question emerged, which was: "What processes control the cross-margin transport of biological, chemical and geological materials in a strongly wind-driven system, viz., the west-coast shelf of the U.S?" These Interdisciplinary Working Group reports are appended to this report (Appendices 1–5) and are the basis for the Science Plan prepared by members of the CoOP steering committee.

II. Science Plan

A. Motivation

The wind has a substantial influence on exchange processes over all of the world's continental margins, although it often appears in addition to other important forcings, such as buoyant runoff from land. Nonetheless, it is the most universally important of forcing functions. It is thus appropriate that CoOP have its first major process study focus on a region where the wind is the predominant forcing mechanism. The improvements that occur in our understanding of biological, chemical and geological processes on such a margin will also enhance the prospects for success in other CoOP studies in other regions.

Characteristics of wind-driven processes over the continental margin

The overriding property of a wind-driven system for consideration by CoOP is that the alongshore wind stress over the water be strong, and that it have substantial variability. It should not be a system that is strongly influenced by river outflows, tidal effects that result in surface-to-bottom mixing, or current variability in the offshore ocean. In such a system, we would expect that most of the current fluctuations would be driven by the wind, either locally, or at a distance through the mechanism of coastal-trapped waves (e.g., Chapman, 1987). The strong onshore–offshore transport driven by the wind in the near-surface turbulent ("Ekman") boundary layer assures rapid cross-margin fluxes, hence short (order of a few days) residence times over the shelf. Despite such short residence times, classic wind-driven systems such as that off Oregon often show strikingly pronounced, persistent biological zonations (Barber and Smith, 1981; Small and Menzies, 1981) that are not understood in terms of how they continue to exist within the dynamic physical setting.

Many of the world's prototypical wind-driven shelf systems, such as the U.S. west coast, the southwestern and northwestern African shelves, the western Iberian peninsula and the west coast of South America, are known for the presence of coastal upwelling during at least one season. In these cases, winds blow alongshore toward the equator, forcing near-surface waters offshore. In turn, deeper waters are drawn onshore and upward, bringing cold, nutrient-rich waters to the surface. Very often, systems

such as these are accompanied by an eastern boundary current (such as the California Current) offshore of the shelf. The cool surface waters chill the air and introduce a very stable marine layer which in turn is prone to a number of unusual effects that are only recently starting to be understood (e.g., Samelson, 1992). The high nutrient levels drive high primary productivity which in turn fuels the entire ecosystem, leading to some of the world's greatest fisheries. Given these high levels of production, it seems likely that these systems have a substantial role in the global carbon cycle (Walsh, 1991). For example, we might expect that air–sea gas fluxes (especially that of carbon dioxide) and the removal of particulate carbon to the sediments would be especially large in these regions. Thus, upwelling shelf systems are globally important for multiple reasons.

One very attractive aspect of seasonally upwelling systems is that there already exists a good set of background information on which to base the design of a modern interdisciplinary effort. For example, the CUEA program of the 1970's collected numerous physical, nutrient and biological measurements in several upwelling systems that help us now to refine hypotheses and to begin new efforts with new technology. Although the measurements made during CUEA did not revolutionize our ideas about upwelling, they were critical in developing a quantitative understanding (and some predictive capability) for sea level and alongshore currents over the shelf. The weakness of the measurements is that they did not resolve cross-margin current variability well, although they demonstrated the importance of doing so in interdisciplinary studies. These results lead us to our present focus on the cross-shelf flow.

Thus, systems that are dominated by wind-driven exchanges are an appropriate and timely place to begin CoOP's large process studies. The systems are important in their own right, there exists good background information with which to start, and the results will surely be relevant to future CoOP efforts.

Why is a wind-driven system study needed?

Our current knowledge of wind-driven coastal systems is incomplete in critical aspects. Our knowledge is best within single disciplines, e.g., physical oceanography, and for upwelling (summer) conditions, which have been studied intensively in the past. But even for physical oceanography, our knowledge is lacking in such areas as the dynamics of fronts or of the exact processes that govern cross-margin exchange.

Further, wintertime (downwelling) conditions are poorly understood in general, despite their importance.

However, CoOP primarily draws its motivation from interdisciplinary issues. Specifically, this CoOP study will address the need for quantitative information on the following subjects:

- The physical, chemical and biological factors that limit primary productivity in wind-driven systems are not well understood. We know that macronutrients (e.g., nitrate) are provided in quantity to the euphotic zone during upwelling conditions, but we have little appreciation for the extent to which nutrient availability, trace chemical contributions, current structures, bloom aggregation processes, and trophic interactions actually limit the abundance of phytoplankton produced. A concentrated study, closely linking contributions from all of the CoOP disciplines is required to reach useful conclusions.

- The relationship of the inner shelf to the broader continental margin system is not well established. The inner shelf (roughly, water shallower than 50 m) is the channel through which much of the transport from deeper waters to the euphotic zone takes place. Further, it is itself a region of high biological productivity, while also being the region most directly affected by anthropogenic influences. Previous studies of upwelling systems have generally neglected this region for logistical reasons, but we are now in a position to try to understand its importance in the overall continental margin context.

- Processes transferring materials to and from the bottom from overlying waters are not well accounted for at present. The facets of this issue are numerous. For example, there is a need to understand how dissolved chemicals and diatom resting stages in the sediments reach the overlying waters and how the waters immediately above the bottom (the bottom boundary layer) are exchanged with overlying interior and near-surface waters. Further, we need to assess mechanisms and rates of incorporation of organic materials into sediments, and the ultimate fates of these materials.

- The role of wind-driven shelf circulation in the global ocean carbon cycle needs to be understood. Coastal upwelling regions are known for their extremely high rates of production, but the ultimate fate of the fixed carbon is not known, in

part, because dynamic physical processes advect upwelled waters away. The sheer volume of production in a coastal upwelling system suggests that, unless the internal recycling of carbon is quite efficient, substantial atmospheric carbon dioxide is removed and transformed into materials that will have an extended residence time in the ocean or sediments.

B. Guiding Questions

The General Question

The above motivations lead to the formulation of a single, broad question to focus a CoOP study of wind-driven shelf regions:

> **What processes control the cross-margin transport of biological, chemical and geological materials in a strongly wind-driven system?**

In order to make this rather broad question more useful, specific questions have been posed under the topics of air–sea interactions, exchanges between the euphotic zone and the ocean interior, plankton distributions and exchanges of materials near the bottom boundary.

Air/Sea Feedbacks

> How do ocean–atmosphere feedbacks act to structure the system?

Wind-driven continental margins often have pronounced and persistent structures within the water column and on the sea floor. For example, fronts in the ocean separate cold and warm surface waters and have well-defined jets (narrow, strong currents that parallel the density front). The water mass boundary is quite likely to affect atmospheric conditions such as inversion height, air temperature and wind speed. On the other hand, it is currently not well known to what extent the wind field acts to determine the location and structure of the front. Likewise, chemical distributions near the air–sea interface can strongly govern air–sea fluxes, that in turn affect atmospheric

cloudiness and oceanic productivity. Air–sea fluxes of heat, momentum and chemicals probably will affect the distribution and strength of primary production over the continental margin. Finally, sediment composition should be affected by air–sea exchange, including inputs of aeolian particles and processes that affect the distribution of biogenic particles.

We are currently making good progress toward understanding how coastal wind patterns are generated, and their sensitivity to atmospheric stability, large-scale winds, and coastal orography. The detailed air–sea feedback determining these processes has not been worked out in any detail, nor has much progress been made on the issue of exactly how 5–100 km scale atmospheric variations affect the ocean system. An example of this type of process is the shelf-scale variations in the wind stress, which can cause localized upwelling and downwelling in the water column well away from the coast. Further, smaller-scale variations of winds stress, surface temperature, sea state and atmospheric stability should help to govern air–sea fluxes of gases and other chemicals. Should such effects prove important, they will strongly influence the physical and chemical systems, and in turn the biological structures.

Research should be directed to the following specific objectives:

- Develop a dynamical and predictive understanding of small-scale (5–100 km) wind patterns in the coastal ocean and how they relate to larger-scale atmospheric variability.
- Understand the spatial variability of the key air–sea fluxes (momentum, heat, gases and other chemicals) and how they are determined by physical, chemical and biological processes.
- Understand how upper ocean currents (including the vertical component) act to determine the temperature, salinity, nutrient and plankton distributions in the critical upper part of the water column, where light is readily available.

Sources and sinks of chemicals in the euphotic zone

> How and where do chemical species enter and leave the euphotic zone from the interior and near-bottom regions?

There are numerous proposed mechanisms by which materials reach the euphotic zone from the deeper water column. The difficulty lies in making quantitative assessments of their relative importance and in developing a useful capability to model or parameterize the important pathways. The most obvious mechanism is the traditional wind-driven upwelling pathway, passing through the inner shelf region out to the shelf and beyond. Other physical pathways include turbulent entrainment into near-surface waters, secondary circulations associated with fronts and eddies, and upwelling induced by spatial variations in the wind stress away from the coast (wind stress curl effects). Further, there exists the possibility of transport through excretions by vertically migrating organisms, and through mass aggregation and sedimentation of diatom blooms. Within this broad range, we need to establish where each mechanism is important: it may be, for example, that a mechanism is not very important over the inner half of the shelf, but that it dominates farther offshore. Finally, much of our thinking on this subject is affected by a bias toward upwelling-favorable wind conditions. We have a good deal less information about what (if any) mechanisms are effective during downwelling conditions.

Particle sinking, downwelling, turbulent mixing and excretion by vertically migrating zooplankton have all been identified as potential mechanisms for removal of materials from the euphotic zone under some conditions. However, their quantitative importance under different physical conditions has not been established for wind-driven coastal systems. Also, over days to weeks, there can be substantial imbalances between inputs and outputs from the upper ocean, leading to material accumulations or deficits that, in turn, affect surface fluxes.

Fluxes into and out of the near-surface region are only part of the issue: we also need to develop an understanding of how materials from the bottom boundary layer and the interior water column reach the euphotic zone. This is important because of the numerous chemical and biological processes that occur at or near the bottom, recycling nutrients and providing a major source of trace chemicals. Many of the pathways are expected to be similar to those for materials in the upper ocean, but the problem is complicated by the presence of the sloping bottom. Water parcels may separate into the interior due to buoyancy anomalies induced by advection within the benthic boundary layer, for example. The potential importance of fluxes from the lower water column is considerable, but they have not yet been systematically evaluated in a strongly wind-driven system.

The strength, location and form in which biologically important materials reach the euphotic zone will be crucial in determining the net biological production. The physical structure, in turn, will be critical in determining the strength and nature of trophic interactions, e.g., where zooplankton grazing is maximum, its role in limiting phytoplankton standing stocks and its contribution to the removal of materials from the near-surface waters. In a sense, the issue of fluxes to and from the euphotic zone is the central issue in wind-driven systems.

The following are important goals for future research:

- Understand and quantify microbial, chemical and photochemical transformations in the euphotic zone that impact both the plankton community and the retention and transport of materials in these coastal regions.
- Evaluate the importance of benthic chemical sources to the euphotic zone in the context of wind-driven systems, and the expected rapid rates of shelf–ocean exchange.
- Establish which chemical constituents are important to the biological system, specifically establishing the role (if any) of micronutrients for regulating the growth and structure of the phytoplankton community.
- Determine the importance of pathways through the strongly turbulent, shallow inner shelf region to the midshelf euphotic zone, and understand the controlling mechanisms (e.g., topographic effects) within the inner shelf.
- Evaluate the relative importance of the entire suite of pathways between turbulent boundary layer regions and the interior region, including entrainment, advection, particle sinking and active biological transport.

Plankton Distributions

How are plankton distribution patterns over the continental margin maintained?

Despite the presumed rapid flushing of water through a wind-driven shelf region, we know that near-surface plankton distribution patterns are surprisingly persistent

(Figure 1, Peterson, Miller and Hutchinson, 1979). These patterns can be stretched and relocated cross-shelf, but are strikingly durable. Physical processes that must influence these patterns include surface Ekman (directly wind-driven) transport, fronts, eddy ("blob") transports, and vertical currents associated with winds or other effects. Nutrient availability also is expected to play a role, in terms of where and in what form nutrients are provided, the role of micronutrients, and the importance of in situ recycling. Grazing, by both zooplankton offshore and benthic animals in the inner shelf, and the rapid mass sedimentation of diatom blooms are expected to be key influences on the net structure of the biological system. Finally, how and where organic matter sinks from the euphotic zone probably governs both the near-surface biological structure and the patterns generated at the bottom.

The importance of this problem results from the high biological production in wind-driven coastal regions. For example, the distribution of plankton undoubtedly affects trophic interactions and helps to govern the degree to which the system supports different fisheries. On a more global basis, the fate of the carbon fixed by the ecosystem depends on the trophic interactions and the existence of preferred locations for particle sinking and sequestration in the sediments.

To achieve a new level of understanding:

- We need a thorough understanding of the three-dimensional near-surface circulation, including the effects of fronts, eddies and locally wind-driven flows.
- The major processes determining the availability of nutrients and any important micronutrients to the euphotic zone need to be quantitatively understood and modeled.
- Spatial and temporal variability in primary production needs to be measured and related to concomitant variability in the suite of physical and biological forcings that determine the fate of plankton in a wind-driven shelf system. These forcings include upwelling/downwelling, grazing rates, sinking, and cross-shore transport.

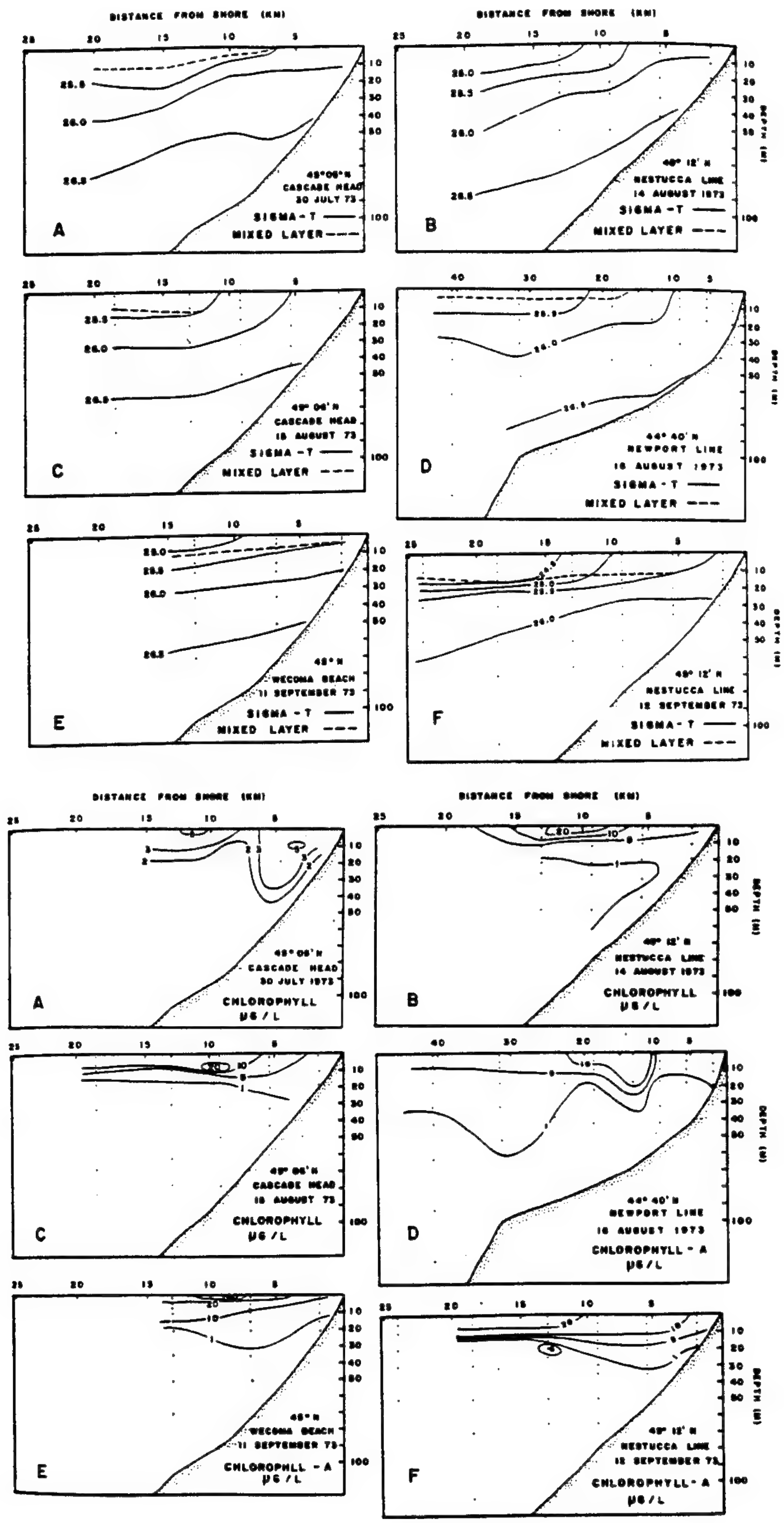


Figure 1: Figures 5 and 6 from Peterson *et al.* (1979).

Benthic Exchanges

> How do exchange processes between the active sediment layer and the water affect the distribution and fate of biologically, chemically and geologically important materials?

The upper part of the shelf's sediment column is the site of active biological and chemical processes that consume some materials from the water column, while sequestering, transforming and recycling others. Materials held in sediments can be efficiently circulated back to the water column either through diffusion or through physical or biological resuspension. Bottom stresses are critical in determining when and how sediment transport takes place. The effectiveness of this transport will depend, in turn, on sediment size distributions, sediment cohesiveness and the biological conditioning of the upper few centimeters. Because of the potential for remobilization of the bottom, processes such as dissolved/particulate organic carbon transformations or microbial processes in sediments can affect the entire water column. On the other hand, we expect that in some locations on the continental margin, the sediments will be a virtually permanent sink for some deposited materials. Whether the bottom serves as a source or sink, we anticipate that benthic processes will affect the entire shelf system.

Benthic processes are expected to be important to the continental margin system in a number of ways. The stress on the flow field by the bottom (which depends on bottom roughness and sediment type, among other factors) helps to govern the amplitude and structure of flows at all depths over the shelf. The bottom also can be a major source of nutrients and other biogeochemically important materials, just as it can be a sink for others, notably carbon. Finally, there is a clear need to improve our knowledge of shelf benthic processes in order to be able to interpret properly the long time series preserved in the sedimentary record.

In order to make progress in understanding the means and extent by which benthic-water column coupling affect cross-shelf material transport:

- We need to understand, as function of location, how deposition rates and the composition of settled materials depend upon the physical, chemical and biological conditions in the overlying waters of the continental margin.

- We need to quantify the relationship between benthic-water column fluxes and governing physical, chemical, biological and geological conditions in both the water column and the sediments.

C. A Plan of Action

1. Introduction

Our approach to the study of processes in a strongly wind-driven system requires close coupling of modeling and observation. The observational component will need about two full years in the field in order to obtain enough data to resolve the temporal extent and variability of processes and to avoid making all observations in a single, possibly unrepresentative, year. The details of how the study is to be made, and where, are discussed in greater detail below. Our general approach is consistent with that outlined in the CoOP science prospectus (Brink *et al.*, 1992) for a process study.

2. Seasonal Setting

On strongly wind-driven shelves, there is often a pronounced seasonality. In the summertime, average wind conditions are usually upwelling-favorable (alongshore, with the coast on the left in the northern hemisphere), while in the wintertime, average winds are downwelling, or only weakly upwelling favorable. However, not all strongly wind-driven coastal regions are sites of persistent upwelling. Off the east coast of the United States, wind-driven effects are clearly present (e.g., Ou *et al.*, 1981), but other processes such as buoyant outflows and offshore influences make these settings more complex.

During upwelling (summertime) conditions, our prototypical shelf is expected to show high biological productivity and many of the other consequences of strong offshore transport in the surface boundary layer. For example, upwelling fronts and eastern boundary currents (such as the California or Benguela) may well be present. Our background understanding for planning a major new field study is best for the upwelling season, since the accumulation of a substantial data base has been stimulated by the well-known biological processes. Although we do not understand the key elements in the quantitative manner that we desire, we presently have enough information off the

west coast of the United States to formulate focussed questions and design sensible sampling plans.

During downwelling (wintertime) conditions, the phenomenology on wind-driven shelves is less well-known. We do know that more energetic winds and waves lead to more active sediment transport processes, and we have a few interesting current records that span the winter. Nonetheless, the details of how the shelf responds to strong winds in downwelling conditions, and the biological and chemical consequences of the response, are not very well known. We anticipate that wintertime conditions are likely to yield some surprises, while at the same time perhaps being more representative of wind-driven processes in regions where upwelling is not a predominant effect.

In summary, both upwelling- and downwelling-dominated conditions have their own reasons for being interesting and important. Thus, a CoOP wind-driven exchange program should take advantage of an environment where both conditions can be observed.

3. Location for a Field Program

The clear consensus of the Portland meeting was that the wind-driven systems field study should take place off the west coast of the United States, and in a location not strongly affected by tidal currents or by fresh water run off from the land. The reasons for this selection are several.

- On the west coast one can find a range of interesting conditions in which wind-driving dominates. For example, off northern California (e.g., just north of San Francisco), there are strong alongshore winds, upwelling fronts quickly move offshore and are rarely observed over the shelf, and there is a well-defined eastern boundary current offshore. Farther north, off central Oregon, average winds are less strongly upwelling favorable during summertime, upwelling fronts are commonly observed over the shelf, and the eastern boundary current offshore is not well-defined.

- There is much historical information available off the west coast, particularly in the fields of meteorology (including the planned CoOP air–sea flux study), physical oceanography and biological oceanography. Thus, it is relatively straightfor-

ward to formulate sampling plans and to experiment with realistic models before the field work.

- Simplicity of logistics: there are numerous convenient ports and staging areas in the region, and none of the difficulties associated with operating in foreign waters.

- Finally, the U.S. west coast is attractive because of the considerable potential for the CoOP science program to cooperate with other efforts, thereby making better use of finite resources. For example, the U.S. GLOBEC program is planning a California Current/eastern boundary current study offshore in the same general region at the same time CoOP expects to be there (U.S. GLOBEC, 1994). Since there is a good deal of intellectual commonality between the two programs, especially in the areas of physical oceanography and plankton dynamics, cooperation seems natural. Cooperation with programs within the National Oceanic and Atmospheric Administration (NOAA) also appears likely, for example involving use of the NOAA data buoys. In addition, there is reason to hope for cooperation with projects funded by the United States Geological Survey, Office of Naval Research, Minerals Management Service and Monterey Bay Aquarium Research Institute.

We do not specify exact locations where field work is to be done, since detailed choices should be made by potential investigators at the time of proposal planning. Nonetheless, the meeting reached a consensus about the general choices of location. First, it was decided that field programs should take place in two contrasting locations simultaneously. The two studies should be done at the same time so that direct contrasts between the two regions can be made without the uncertainties that are known to be introduced off the west coast by year to year variability, e.g., those associated with El Niño. The two settings can be contrasted as follows:

- Northern California ("less frontal"): During the summertime, fronts are generally not found over the shelf. Rather, as upwelling continues, the front appears to progress far offshore and merge with the core California Current jet studied by the Coastal Transition Zone (CTZ) program (Brink and Cowles, 1991). The primary wind-driven dynamics, while strongly of an upwelling character, are not strongly involved with frontal processes. Wintertime conditions have episodic

downwelling but frontal effects associated with persistent downwelling are not likely to be present.

- Central Oregon ("strongly frontal"): A location should be chosen where fronts are usual over the shelf for most of the upwelling season, but where separation of the frontal jet from the shelf can be expected to occur at some time. This would allow study of an upwelling region where frontal dynamics are important for determining upper ocean characteristics. In addition, at this latitude, persistent downwelling is expected to occur throughout the winter, so any interesting frontal effects or boundary layer instabilities associated with persistent downward heat advection should be pronounced.

While the above contrasts deal mainly with physical characteristics, it seems fairly clear that different physical environments (e.g., frontal versus non-frontal) will present different biological and chemical structures. Once again, the ability to contrast settings presents new opportunities for biological, chemical and geological insights.

While it seems clear that two, three-dimensional coastal areas should be studied simultaneously, it should be left to the scientists who do the work how resources should be split between the locations. For example, it might prove advantageous either to use matched resources at the two sites or to concentrate on one location and stage a minimal effort, sufficient to allow sensible contrasts, at the other.

4. Modeling

Modeling will be important throughout the wind-driven system study: in the formulation stages, during the field work and during the analysis and synthesis stage. Models allow hypotheses to be refined and sampling plans to be tested. They can play a role in isolating critical inputs and the weakest points in our understanding, thus leading to the concentration of resources on particular issues. Models can help to direct observations in real time, and they can interpolate observations into a more complete picture of processes. Finally, models are expected to be the quantitative expression of the results of the overall interdisciplinary effort.

The call for modeling is not restricted to numerical modeling. There are a number of useful approaches to modeling: conceptual, laboratory, analytical and numerical.

The important concerns are that the CoOP modeling effort be tightly linked with the observational effort, and that a continuous iterative process between models and observations take place.

There is a wide variety of modeling topics that would be useful to explore, but the following ones would be especially useful to have underway before a major field program is completely designed.

- The physical processes that govern separation of the upwelling front from the coast need to be understood in terms of the relative roles of topographic irregularities versus wind forcing.

- The possible causes of secondary circulations at fronts need to be explored, especially with regard to predicting when they might be prominent.

- Two-dimensional models of downwelling (Allen *et al.*, in preparation) suggest dramatic effects, especially near the bottom. Existing process-oriented models need to be extended to more realistic three-dimensional conditions to see if the novel effects are replicated.

- The role of topographic irregularities for governing horizontal and vertical transport in the shallow and turbulent inner shelf (depth less than roughly 30 m) need to be explored.

- A physical–biological model needs to be developed that addresses the rates of phytoplankton and zooplankton growth under representative conditions of advection and mixing.

- A coupled physical–biological trophic interaction model that includes microbes and dissolved organic carbon (DOC) needs to be used to make preliminary assessments of these issues, which have not normally been considered in a wind-driven continental margin setting.

- Spatially dependent sediment transport processes need to be explored, as a step toward a quantitative understanding of how sediment distribution patterns over the shelf and slope develop. Such a model should also include processes such as particle settling, aggregation and disaggregation, and physical, biological and chemical effects on sediment composition.

- For all disciplines, data-assimilative studies should be carried out in order to understand the data-gathering requirements for a field program that will answer the questions outlined in section II.B.

5. Observations

The objectives of the observational program are twofold:

- Monitor the distributions of key variables (meteorological, biological, chemical, geological and physical) in three dimensions and over time with sufficient resolution. Coverage must account for the possibility that special locations or temporal events may dominate particular processes.
- Measure and parameterize the rates that govern changes in key variables. For example, this could include air–sea fluxes, or rates of grazing, plankton growth or sedimentation.

A well-designed field program should provide a thorough description of processes and the ability to answer the questions posed above. It should also be able to provide information needed to run and test models, since models are a means to extrapolate information to a broader temporal or spatial setting.

The following two sections provide some guidance as to the types of measurements that will prove useful, and how they could be conducted. The description is meant to suggest the desirable scale and scope of measurements, rather than to define a detailed field program. Our understanding and technology are likely to change before a field program starts, so the exact nature of the final study must be left to the investigators who carry out the research.

Fixed-Site Measurements

Measurements at a fixed site, often using moorings, provide the considerable benefit of good temporal resolution, but with the drawback of poor or nonexistent spatial resolution. Thus, the fixed-site observations suggested below are to be seen as part of a broader program that involves good spatial resolution through either ship-based measurements or remote sensing. Nevertheless, time series measurements at a set location are critical: they fill any gaps from other sorts of measurements, resolve strong

episodic events, provide some information about the persistence of spatial patterns, and, in some cases, make observations that are impractical by any other means.

Objectives of a fixed site program must include the following:

- Resolve how flow closes in the inner shelf region, i.e., is there a tendency for horizontal or vertical cells?
- Measure transports in the bottom boundary layer as a function of both alongshore and cross-margin position.
- Measure downward fluxes of particulates over both the shelf and slope. This could require novel approaches in the energetic shelf environment.
- Provide information needed to estimate horizontal fluxes, hence close budgets of biologically, chemically or geologically important variables.
- Measure major forcing functions and process rates of the system.

Moored measurements should provide resolution with depth, alongshore and cross-margin position. At least one heavily instrumented surface meteorological package should be maintained, with enough instrumentation to measure surface heat and momentum transfer as well as (technology allowing) important chemical fluxes. Subsurface moorings should be designed, to the extent possible, to resolve vertical distributions of currents, nutrients, dissolved gases, plankton and important optical properties. Acoustic Doppler systems will be especially useful because they measure both currents and a proxy zooplankton biomass. All moorings should be maintained for the entire two-year period of the field study.

Shore-based measurements can also be very important to the study. Coastal sea level data from tide gauges provide evidence of coastal trapped waves and anomalous oceanic conditions such as El Niño. Radar-based systems can measure radial wind components during rain, and other radar systems can be used to map surface currents over a substantial spatial domain.

Underway Observations

Underway surveys of important variables can be made from either ship or aircraft. Speed is often of the essence in making such measurements in order to obtain useful

"snap shots" that are not contaminated by rapid time changes. Thus, meteorological measurements are best made in a few hours to avoid aliasing by diurnal variability, and ship-based surveys are best to be completed in a day or less. Such surveys, repeated many times, allow invaluable time series of spatial structures, but with the drawback of substantial temporal gaps. These measurements are essential for resolving such important, but highly mobile features, as fronts.

Aircraft measurements can provide observations of winds, surface temperature, turbulence, boundary layer structure and ocean color. Further, measurements that help to resolve spatial patterns of air–sea chemical fluxes are highly desirable.

Ship-based measurements can make good use of today's ability to carry out underway hydrographic measurements using towed bodies. Doppler-acoustic profiles of currents, temperature, salinity, chlorophyll, light transmission, and incoming radiation should all be measured. The variables needed to estimate surface air–sea fluxes should be monitored at the same time. Acoustic and/or optical plankton counters are also desirable. In addition, the ship's water intake can be used to observe patterns of plankton, nutrients and other chemical constituents. Bottom conditions can be mapped underway using sophisticated sonar systems.

Near surface drifters, to be deployed primarily from ships, are a powerful tool for studying cross-shelf transport processes. Large deployments of lightly-instrumented drifters have been very useful for determining circulation patterns and locations of convergence (such as fronts and jets). Drifters equipped with optical instrumentation have the capability of quantifying biological growth as upwelled water moves across the continental margin. The value of Lagrangian measurements is considerably increased if results can be studied in the context of supporting information, particularly from remote-sensing satellites.

A number of important variables can not be measured without stopping the ship. For example, zooplankton net samples, many chemical species including radionuclides, soft-bodied plankton, microbial processes, detailed nutrient profiles, and benthic studies will require the ship to stay on station, sometimes for substantial times. These measurements are often needed to supply the rate information required to make sense of distributions observed. For this reason, a second ship should be made available for time-consuming measurements so that these will not limit the ability to conduct rapid surveys.

Finally, the role of satellite remote sensing is crucial. The good spatial coverage, synopticity and continuing availability of these observations makes them an essential part of any coastal field study. The sensors that are most valuable are those for surface temperature and ocean color. These systems resolve key spatial structures that provide excellent time series in their own right, while simultaneously providing guidance for ship-based observers.

D. Conclusions

The Portland meeting specified the ideas that would drive a major field study of coastal processes in a region where wind-driven exchanges predominate. The field work outlined by the various interdisciplinary groups and recapitulated in this section is quite ambitious and broadly defined. Those who actually carry out the research will have to make choices in order to make the effort into a well-defined, tight field program. By the time proposals are requested, many things could change in our technology, dynamical understanding and available observational results. For this reason, too, the ultimate workers need to be allowed flexibility to deviate from the ideas outlined above, as new findings warrant. Finally, we reiterate the need to have some efforts start soon: all of the modeling efforts outlined above should be started well before the field program is actually designed, and some work on novel approaches to observations is also important.

III. Epilogue

The consensus of the workshop was that a CoOP study of wind-driven transport processes should be made and should take place over the continental margin adjacent to the U.S. west coast. The effect of strong alongshore wind in driving the coastal currents and the resulting cross-shelf transport in the surface and bottom boundary layers is of first-order importance in determining the cross-margin transport along the U.S. west coast. The ubiquity of wind forcing on all continental shelves, and the importance of its effects, makes it an appropriate focus of the first CoOP major process study. The dynamical and ecological analogues between the west coasts of the Americas, Africa, and the Iberian peninsula give global significance to a study off the west coast of the U.S. That there are major scientific problems in the coastal ocean still to be addressed, yet ripe for investigation because of advances in observational technology and modeling, was clearly manifest during the workshop and is apparent in the interdisciplinary working group reports: Bottom Boundary Layer Processes (Appendix 1), Inner Shelf Processes (Appendix 2), Upper Ocean Processes (Appendix 3), Interior Water Column Processes (Appendix 4), and Frontal Processes (Appendix 5). The studies suggested by the interdisciplinary working groups have been restated in the Science Plan.

Thus, the stage is set: we now have the capability and understanding to carry out a definitive interdisciplinary study of processes related to wind-driven exchange over continental margins. The western coast of the United States represents a nearly perfect natural laboratory with convenient logistics and a large historical data base to help plan field work confidently. At the open Portland meeting, a large group of scientists reached consensus on what, how, and where work should be done.

References (including for Appendices)

Alldredge, A. L., and C. C. Gottschalk, 1989. Direct observations of the mass flocculation of diatom blooms: characteristics, settling velocities, and formation of diatom aggregates. *Deep-Sea Research*, **36**, 159–171.

Allen, J. S., 1973. Upwelling and coastal jets in a continuously stratified ocean. *Journal of Physical Oceanography*, **3**, 245–257.

Allen, J. S., P. A. Newberger, and J. Federiuk, Downwelling circulation on the Oregon continental shelf: Part 1, response to idealized forcing. In preparation.

Allison, M., 1993. Mechanisms of Coastal Progradation and Muddy Strata Formation Adjacent to the Amazon River. Ph.D. Dissertation, State University of New York, Stonybrook, New York, 322 pp.

Bacon, M. P., R. A. Belastock, and M. H. Bothner, 1994. Lead-210 balance and implications for particle transport on the continental shelf, Middle Atlantic Bight. *Deep-Sea Research II*, in press.

Bannister, T. T., 1974. Production equations in terms of chlorophyll concentration, quantum yield, and upper limit to production. *Limnology and Oceanography*, **19**, 1–12.

Barber, R. T., and R. L. Smith, 1981. Coastal upwelling ecosystems. In: *Analysis of Marine Ecosystems*, edited by A. R. Longhurst, Academic Press, 31–68.

Beardsley, R., C. Dorman, C. Friehe, L. Rosenfeld, and C. Winant, 1987. Local atmospheric forcing during CODE. Part 1: A description of the marine boundary layer and atmospheric conditions over a northern California upwelling region. *Journal of Geophysical Research*, **92**, 1467–1488.

Berger, W. H., 1976. Biogenous deep sea sediments: Production, preservation, and interpretation. In: *Chemical Oceanography*, Vol. **5**, J. P. Riley and R. Chester, editors, Academic Press, 265–388.

Biasco, D., M. Estrada, and B. H. Jones, 1981. Short time variability of phytoplankton populations in upwelling regions — the example of northwest Africa. In: *Coastal Upwelling*, F. A. Richards, editor, American Geophysical Union, Washington, D. C., pp. 339–347

Blanton, J. O., 1981. Ocean currents along a nearshore frontal zone on the continental shelf of the southeastern U.S. *Journal of Physical Oceanography*, **11**, 1627–1637.

Bosart, L. F., V. Pagnotti, and B. Lettau, 1973. Climatological aspects of eastern United States back-door cold frontal passages. *Monthly Weather Review*, **101**, 627–635.

Brink, K. H., 1991. Coastal-trapped waves and wind-driven currents over the continental shelf. *Annual Review of Fluid Mechanics*, **23**, 389–412.

Brink, K. H., J. M. Bane, T. M. Church, C. W. Fairall, G. L. Geernaert, D. E. Hammond, S. M. Henrichs, C. S. Martens, C. A. Nittrouer, D. P. Rogers, M. R. Roman, J. D. Roughgarden, R. L. Smith, L. D. Wright, and J. A. Yoder, 1992. Coastal Ocean Processes: A Science Prospectus. *Woods Hole Oceanographic Institution Technical Report*, WHOI-92-18, 88 pp.

Brink, K. H., and T. Cowles, 1991. The Coastal Transition Zone Program. *Journal of Geophysical Research*, **96**(C8), 14,637–14,647.

Brink, K. H., J. H. LaCasce and J. D. Irish, 1994. The effect of short-scale wind variations on shelf currents. *Journal of Geophysical Research*, **99**, 3305–3315.

Bruland, K. W., 1980. Oceanographic distributions of cadmium, zinc, nickel, and copper in the North Pacific. *Earth and Planetary Science Letters*, **47**, 176–198.

Bruland, K. W., J. R. Donat, and D. A. Hutchins, 1991. Interactive influences of bioactive trace metals on biological production in oceanic waters. *Limnology and Oceanography*, **36**, 1555–1577.

Cacchione, D. A., and D. E. Drake, 1979. A new instrument system to investigate sediment dynamics on continental shelves. *Marine Geology*, **30**, 299–312.

Cacchione, D. A., and D. E. Drake, 1982. Measurements of storm-generated bottom stresses on the continental shelf. *Journal of Geophysical Research*, **87**, 1952–1960.

Cacchione, D. A., and D. E. Drake, 1990. Shelf sediment transport: An overview with applications to the northern California continental Shelf. In: *The Sea*, 9 Part B, B. LeMehaute and D. M. Hanes, editors, Wiley Interscience, New York, 729–773.

Carpenter, R., J. T. Bennett, and M. L. Peterson, 1981. 210Pb activities in and fluxes to sediments of the Washington continental shelf and slope. *Geochemica et Cosmochimica Acta*, **45**, 1155–1172.

Chapin, T. P., K. S. Johnson and K. H. Coale, 1991. Rapid determination of manganese in seawater by flow injection analysis with chemiluminescence detection. *Analytica Chimica Acta*, **249**, 469–478.

Chapman, D. C., 1987. Application of wind-forced, long, coastal-trapped wave theory along the California coast. *Journal of Geophysical Research*, **92**, 1798–1816.

Chavez F. P., R. T. Barber, P. M. Kosro, A. Huyer, S. R. Ramp, T. P. Stanton, and B. Rojas de Mendiola, 1991. Horizontal transport and the distribution of nutrients in the coastal transition zone off northern California: Effects on primary productivity, phytoplankton biomass, and species composition. *Journal of Geophysical Research*, **36**, 14,833–14,848.

Coale, K. H., C. S. Chin, G. J. Massoth, K. S. Johnson, and E. T. Baker, 1991. In situ chemical mapping of dissolved iron and manganese in hydrothermal plumes. *Nature*, **352**, 325–328.

Davis, R. E., 1985a. Drifter observations of coastal surface currents during CODE: The method and descriptive view. *Journal of Geophysical Research*, **90**, 4741–4755.

Davis, R. E., 1985b. Drifter observations of coastal surface currents during CODE: The statistical and dynamical views. *Journal of Geophysical Research*, **90**(C3), 4756–4772.

Dickey, T., J. Marra, T. Granata, C. Langdon, M. Hamilton, J. Wiggert, D. Siegel and A. Bratkovich, 1991. Concurrent high resolution bio-optical and physical time series observations in the Sargasso Sea during the spring of 1987. *Journal of Geophysical Research*, **96**, 8643–8663.

Dorman, C. E., 1985. Evidence of Kelvin waves in California's marine layer and related eddy generation. *Monthly Weather Review*, **113**(5), 827–839.

Dorman, C. E., 1987. Possible role of gravity currents in northern California's coastal summer wind reversals. *Journal of Geophysical Research*, **92**, 1497–1506.

Drake, D. E., and D. A. Cacchione, 1987. Suspended particulate matter along the Coastal Ocean Dynamics Experiment central line during upwelling and relaxation events. *Journal of Geophysical Research*, **92**(C2), 1699–1707.

Elliott, D. L., and J. J. O'Brien, 1977. Observational studies of the marine boundary layer over an upwelling region. *Monthly Weather Review*, **105**, 86–98.

Enriquez, A., and C. A. Friehe, 1991. Variability of the atmospheric boundary layer over a coastal shelf in winter during SMILE. In; *Fifth Conference on Meteorology and Oceanography of the Coastal Zone*, American Meteorological Society, Boston, 102–107.

Fairall, C. W., and S. E. Larsen, 1986. Inertial-dissipation methods and turbulence fluxes at the air–ocean interface. *Boundary Layer Meteorology*, **11**, 19–38.

Falkowski, P. G, R. M. Greene, and R. J. Geider, 1992. Physiological limitations on phytoplankton productivity in the ocean, *Oceanography*, **5**(2), 84–91.

Flegal, A. R., T. F. Duda, and S. Niemeyer, 1989. High gradients of lead isotopic composition in northeast Pacific upwelling filaments. *Nature*, **339**, 458–460.

Forbes, G. S., R. A. Anthes, and D. W. Thomson, 1987. Synoptic and mesoscale aspects of an Appalachian ice storm associated with cold-air damming. *Monthly Weather Review*, **115**, 564–491.

Friederich, G. E., 1994. Seasurface pCO_2 measurements in a coastal upwelling system. *EOS, Transactions of the American Geophysical Union*, **85**, 60.

Friehe, C. A., W. J. Shaw, D. P. Rogers, K. L. Davidson, W. G. Large, S. A. Stage, G. H. Crescenti, S. J. S. Hkalsa, G. K. Greenhut, and F. Li, 1991. Air–sea fluxes and surface-layer turbulence around a sea surface temperature front. *Journal of Geophysical Research*, **96**, 8593–8609.

Glenn, S. M., 1983. A Continental Shelf Bottom Boundary Layer Model: The Effect of Waves, Currents, and a Moveable Bed. Woods Hole Oceanographic/Massachusetts Institute of Technology Joint Program in Oceanography and Ocean Engineering, 237 pp.

Glenn, S. M., and W. D. Grant, 1987. A suspended sediment stratification correction for combined wave and current flows. *Journal of Geophysical Research*, **92**, 8242–8264.

Grant, W. D., and O. S. Madsen, 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research*, **84**, 1797–1808.

Grant, W. D., and O. S. Madsen, 1982. Movable bed roughness in unsteady oscillatory flow. *Journal of Geophysical Research*, **87**, 469–481.

Grant, W. D., and O. S. Madsen, 1986. The continental shelf bottom boundary layer. *Annual Review of Fluid Mechanics*, **18**, 265–305.

Grant, W. D., A. J. Williams, III, and S. M. Glenn, 1984. Bottom stress estimates and their prediction on the northern California continental shelf during CODE-1: The importance of wave-current interaction. *Journal of Physical Oceanography*, **14**, 506–527.

Halpern, D., 1974. Variations in the density field during coastal upwelling. *Tethys*, **6**, 363–374.

Halpern, D., 1976. Structure of a coastal upwelling event observed off Oregon during July 1973. *Deep-Sea Research*, **23**, 495–508.

Hayes, S. P., and D. Halpern, 1976. Observations of internal waves and coastal upwelling off the Oregon coast. *Journal of Marine Research*, **34**, 247–267.

Healy Ridge, M. J., and B. Carson, 1987. Sediment transport on the Washington continental shelf: estimates of dispersal rates from Mount St. Helens ash. *Continental Shelf Research*, **7**, 759–772.

Hermann, A. J., B. M. Hickey, M. R. Landry, and D. F. Winter, 1989. Coastal upwelling dynamics. In: *Coastal Oceanography of Washington and Oregon*, M. R. Landry and B. M. Hickey, editors, Elsevier, Amsterdam, 211–253.

Hickey, B. M., 1989. Patterns and processes of circulation over the shelf and slope. In: *Coastal Oceanography of Washington and Oregon*, M. R. Landry and B. M. Hickey, editors, Elsevier, Amsterdam, Netherlands, 41–115.

Hickey, B. M., 1992. Circulation over the Santa Monica–San Pedro basin and shelf. *Progress in Oceanography*, **30**, 37–115.

Hirayama K., and N. Unohara, 1988. Spectrophotometric catalytic determination of an ultratrace amount if iron (III) in water based on the oxidation of N,N-dimethyl-p-phenylenediamine by hydrogen peroxide. *Analytical Chemistry*, **60**, 2573–2577.

Hobbs, P. V., 1987. The Gulfstream rainband. *Geophysical Research Letters*, **14**, 1142–1145.

Hobbs, P. V., T. J. Matejka, P. H. Herzegh, J. D. Locatelli, and R. A. Houze, Jr., 1980. The mesoscale and microscale structure and organization of clouds and precipitation in mid-latitude cyclones. I. A case study of a cold front. *Journal of Atmospheric Sciences*, **37**, 586–596.

Hood, R. R., 1990. Phytoplankton biomass, photosynthetic light responses, and physical structure in a northern California upwelling system. Ph.D. dissertation, University California San Diego, 141 pp.

Hood, R. R., M. R. Abbott, A. Huyer, and P. M. Kosro, 1990. Surface patterns in temperature, flow, phytoplankton biomass, and species composition in the Coastal Transition Zone off Northern California. *Journal of Geophysical Research*, **95**, 18,081–18,094.

Hood, R. R., M. R. Abbott, and A. Huyer, 1991. Phytoplankton and photosynthetic light response in the coastal transition zone off northern California in June 1987. *Journal of Geophysical Research*, **96**, 14,769–14,780.

Hood, R. R., S. Neuer, and T. J. Cowles, 1992. Autotrophic production, biomass and species composition across an upwelling front. *Marine Ecological Program Series*, **83**, 221–232.

Howells, P. A. C., and Y.-H. Kuo, 1988. A numerical study of the mesoscale environment of a southerly buseter event. *Monthly Weather Review*, **116**, 1171–1178.

Huyer, A., 1984. Hydrographic observations along the CODE Central Line off northern California, 1981. *Journal of Physical Oceanography*, **14**, 1647–1658.

Huyer, A., P. M. Kosro, J. Fleischbein, S. E. Ramp, T. Stanton, L. Washburn, F. P. Chavez, T. J. Cowles, S. D. Pierce, and R. L. Smith, 1991. Currents and water masses of the coastal transition zone off northern California, June to August, 1988. *Journal of Geophysical Research*, **96**(C8), 14,809–14,831.

Jamart, B. M., D. F. Winter, K. Banse, G. C. Anderson, and R. K. Lam, 1977. A theoretical study of phytoplankton growth and nutrient distribution in the Pacific Ocean off the northwestern U.S. coast. *Deep-Sea Research*, **24**, 753–773.

Jannasch, H. W., C. M. Sakamoto, and K. S. Johnson, 1994. Continuous nitrate neasurements obtained by osmotically pumped in situ long-term sensors. *EOS, Transactions of the American Geophysical Union*, **75**, 42.

Johnson, D. R., B. S. Hester, and J. R. McConnaughey, 1984. Studies of a wind mechanism influencing the recruitment of blue crabs in the Middle Atlantic Bight. *Continental Shelf Research*, **3**, 425–437.

Johnson, K. S., C. M. Sakamoto-Arnold, and C. L. Bechler, 1990. Continuous determination of nitrate concentrations in situ. *Deep-Sea Research*, **36**, 1407–1413.

Jumars, P. A., 1993. *Concepts in Biological Oceanography, An Interdisciplinary Primer*. Oxford University Press, Inc., New York, 384 pp.

Kachel, N. B., and J. D. Smith, 1986. Geologic impact of sediment transporting events on the Washington continental shelf. In: *Shelf Sands and Sandstones, Memoir II*, R. J. Knight and J. R. McLean, editors, Canadian Society of Petroleum Geologists, Calgary, pp. 145–162.

Kachel, N. B., and J. D. Smith, 1989. Sediment transport and deposition on the Washington continental shelf. In: *Coastal Oceanography of Washington and Oregon*, 47, M. R. Landry and B. M. Hickey, editors, Elsevier, Amsterdam, pp. 287–348.

Kadko, D. C., L. Washburn, and B. Jones, 1991. Evidence of subduction within cold filaments of the northern California coastal transition zone. *Journal of Geophysical Research*, **96**, 14,909–14,926.

Keen, T. R., and R. L. Slingerland, 1993a. A numerical study of sediment transport and event bed genesis during tropical storm Delia. *Journal of Geophysical Research*, **98**(C3), 4775–4791.

Keen, T. R., and R. L. Slingerland, 1993b. Four storm-event beds and the tropical cyclones that produced them: a numerical hindcast. *Journal of Sedimentary Petrology*, **63**(2), 218–232.

Kelly, K. A., 1985. The influence of winds and topography on the sea surface temperature patterns over the Northern California Slope. *Journal of Geophysical Research*, **90**, 11,783–11,798.

Kiefer, D. A., and B. G. Mitchell, 1983. A simple steady state description of phytoplankton growth based on absorption cross section and quantum efficiency. *Limnology and Oceanography*, **28**, 770–776.

Kokkinakis, S. A., and P. A. Wheeler, 1987. Nitrogen uptake and phytoplankton growth in coastal upwelling regions. *Limnology and Oceanography*, **32**, 1112–1123.

Kosro, P. M., 1987. Structure of the coastal current field off northern California during the Coastal Ocean Dynamics Experiment. *Journal of Geophysical Research*, **92**, 1637–1654.

Kundu, P. K., and J. S. Allen, 1976. Some three-dimensional characteristics of low-frequency current fluctuations near the Oregon coast. *Journal of Physical Oceanography*, **6**, 181–199.

Landry, M. R., J. R. Postel, W. K. Peterson, and J. Newman, 1989. Broad-scale distributional patterns of hydrographic variables on the Washington–Oregon Shelf. In: *Coastal Oceanography of Washington and Oregon*, M. R. Landry and B. M. Hickey, editors, Elsevier, Amsterdam, 1–40.

Lentz, S. J., 1992. The surface boundary layer in coastal upwelling regions. *Journal of Physical Oceanography*, **22**, 1517–1539.

Lentz, S. J., and J. H. Trowbridge, 1991. The bottom boundary layer over the northern California shelf. *Journal of Physical Oceanography*, **21**, 1186–1201.

Lentz, S. J., and C. D. Winant, 1986. Subinertial currents on the southern California shelf. *Journal of Physical Oceanography*, **16**, 1737–1750.

MacCready, P., and P. B. Rhines, 1991. Buoyant inhibition of Ekman transport on a slope and its effects on stratified spin-up. *Journal of Fluid Mechanics*, **223**, 631–661.

Mantoura, R. F. C., J.-M. Martin, and R. Wollast, editors, 1991. *Dahlem Workshop Reports; Physical, Chemical and Earth Sciences Research Report 9* "Ocean Margin Processes in Global Change," March 18–23, 1990, Berlin.

Margalef, R., 1978. Phytoplankton communities in upwelling areas. The example of NW Africa. *Oecologia Aquatica*, **3**, 97–132.

Marra, J., W. S. Chamberlin, and C. Knudson, 1993. Proportionality between in situ carbon assimilation and bio-optical measures of primary production in the Gulf of Maine in summer. *Limnology and Oceanography*, **38**, 232–238.

Martin, J. H., and R. M. Gordon, 1988. Northeast Pacific iron distributions in relation to phytoplankton productivity. *Deep-Sea Research*, **35**, 177–196.

Mass, C. F., and G. K. Ferber, 1990. Surface pressure perturbations produced by an isolated mesoscale topographic barrier. Part 1: General characteristics and dynamics. *Monthly Weather Review*, **118**, 2579–2596.

McConnaughey, R. A., D. A. Armstrong, B. M. Hickey, and D. R. Gunderson, 1992. Juvenile Dungeness crab, Cancer magister, recruitment variability and oceanic transport during the pelagic larval phase. *Canadian Journal of Fisheries and Aquatic Sciences*, **49**, 2,028–2,044.

Mitchum, G. T., and A. J. Clarke, 1986. The frictional nearshore response to forcing by synoptic scale winds. *Journal of Physical Oceanography*, **16**, 934–946.

Mizzi, A. P., and R. A. Pielke, 1984. A numerical study of the mesoscale atmospheric circulation observed during a coastal upwelling event on 23 August 1972. Part I; Sensitivity studies. *Monthly Weather Review*, **112**, 76–90.

Mooers, C. N. K., C. A. Collins, and R. L. Smith, 1976. The dynamic structure of the frontal zone in the coastal upwelling region off Oregon. *Journal of Physical Oceanography*, **6**, 3–21.

Morel, F. M. M., R. J. M. Hudson, and N. M. Price, 1991. Limitation of productivity by trace metals in the sea. *Limnology and Oceanography*, **36**, 1742–1755.

Nelson, C. S., 1977. Wind stress and wind stress curl over the California Current. NOAA Technical Report NMFS SSRF-714, 87 pp.

O'Brien J. J., B. M. Woodworth, and D. J. Wright, 1974. The Coho project, II. Environmental report. Joint report of Florida State University and Oregon State University, 116 pp.

Onken, R., 1990. The creation of reversed baroclinicity and subsurface jets in oceanic eddies. *Journal of Physical Oceanography*, **20**, 786–791.

Ou, H. W., R. C. Beardsley, D. Mayer, W. C. Boicourt, and B. Butman, 1981. An analysis of subtidal current fluctuations in the Middle Atlantic Bight. *Journal of Physical Oceanography*, **11**(10), 1383–1392.

Overland, J. E., and B. A. Walter, 1981. Gap winds in the Strait of Juan de Fuca. *Monthly Weather Review*, **109**, 2221–2233.

Peterson, W. F., C. B. Miller, and A. Hutchinson, 1979. Zonation and maintenance of copepod populations in the Oregon upwelling zone. *Deep-Sea Research*, **26A**, 467–494.

Pollard, R. T., and L. A. Regier, 1992. Vorticity and vertical circulation at an ocean front. *Journal of Physical Oceanography*, **22**, 609–625.

Pomeroy, L. R., J. O. Blanton, G. A. Poffenhofer, K. L. Von Damm, P. G. Verity, H. L. Windom, and T. N. Lee, 1993. Inner shelf processes. In: *Ocean Processes: U.S. Southeast Continental Shelf*, D. W. Menzel, editor, A summary of research conducted in the South Atlantic Bight under the auspices of the U. S. Department of Energy from 1977 to 1991. U.S. Dept. of Energy, Office of Scientific and Technical Information; Oak Ridge TN, pages 9–43.

Rothschild, B. J., and T. R. Osborn, 1988. Small scale turbulence and plankton contact rates. *Journal of Plankton Research*, **10**(3), 465–474.

Rotunno, R. (Chair), J. A. Curry, C. W. Fairall, C. A. Friehe, W. A. Lyons, J. E. Overland, R. A. Pielke, D. P. Rogers, and S. A. Stage, Panel on Coastal Meteorology, 1992. *Coastal Meteorology. A Review of the State of the Science*, National Academy Press, Washington, D.C., 99 pp.

Roughgarden, J., S. Gaines, and H. Possingham, 1988. Recruitment dynamics in complex life cycles. *Science*, **241**, 1460–1466.

Sakamoto-Arnold, C. M., and K. S. Johnson, 1987. Determination of picomolar levels of cobalt in seawater by flow injection analysis with chemiluminescence detection. *Analytical Chemistry*, **59**, 1789–1794.

Samelson, R. M., 1992. Supercritical marine layer flow along a smoothly-varying coastline. *Journal of the Atmospheric Sciences*, **49**, 1571–1584.

Small, L. F., and D. W. Menzies, 1981. Patterns of primary productivity and biomass in a coastal upwelling region. *Deep-Sea Research*, **28A**, 123–149.

Small, L. F., H. Pak, D. M. Nelson, and C. S. Weimer, 1989. Seasonal dynamics of suspended particulate matter. In: *Coastal Oceanography of Washington and Oregon*, M. R. Landry and B. M. Hickey, editors, Elsevier, Amsterdam, 255–295.

Smith, J. D., 1977. Modeling of sediment transport on continental shelves. In: *The Sea*, 6, E. D. Goldberg, I. N. McCave, J. J. O'Brien and J. H. Steele, editors, Wiley-Interscience, New York, 539–577.

Smith, R. L., 1981. A comparison of the structure and variability of the flow field in three coastal upwelling regions: Oregon, Northwest Africa, and Peru. In: *Coastal Upwelling*, Francis A. Richards, editor, *Coastal and Estuarine Sciences*, **1**, American Geophysical Union, Washington, D.C., pp. 107–118.

Smith, S. D., 1988. Coefficients for sea surface wind stress, heat flux, and wind profiles as a function of wind speed and temperature. *Journal of Geophysical Research*, **93**, 467–472.

Stevenson, M. R., R. Garvine, and B. Wyatt, 1974. Lagrangian measurements in a coastal upwelling zone off Oregon. *Journal of Physical Oceanography*, **4**, 321–336.

Sunda, W. G., 1988. Trace metal interactions with marine phytoplankton. *Biological Oceanography*, **6**, 411–442.

Thomas, A. C., F. Huang, P. T. Strub, and C. James, 1994. A comparison of the seasonal and interannual variability of phytoplankton pigment concentrations in the Peru and California Current systems. *Journal of Geophysical Research*, **99**, 7355–7370.

Traganza, E. D., D. G. Redalje, and R. W. Garwood, 1987. Chemical flux, mixed layer entrainment and phytoplankton blooms at upwelling fronts in the California coastal zone. *Continental Shelf Research*, **7**, 89–105.

Trowbridge J. H., and S. J. Lentz. 1991. Asymmetric behavior of an oceanic boundary layer above a sloping bottom. *Journal of Physical Oceanography*, **21**, 1171–1185.

U.S. GLOBEC, 1994. Eastern boundary current program — A science plan for the California Current. Report 11, U.S. Global Ocean Ecosystems, Dynamics, in press.

van Geen, A., S. N. Luoma, C. C. Fuller, R. Amina, H. E. Clifton, and S. Trumbore, 1992. Evidence from Cd/Caratios in foraminifera for greater upwelling off California 400 years ago. *Nature*, **358**, 54–56.

Wakeham S. G., and C. Lee, 1992. Production, transport and alteration of particulate organic matter in the marine water column. In: *Organic Geochemistry*, edited by M. H. Engel and S. a. Macko, Plenum Press, 145–169.

Wallace, D. W. R., and C. D. Wirick, 1992. Dissolved O_2 time-series records large air–sea gas fluxes associated with breaking waves. *Nature*, **356**, 694–696.

Walsh, J. J., 1991. Importance of continental margins in the marine biogeochemical cycling of carbon and nitrogen. *Nature*, **350**, 53–55.

Walsh, J. J., T. E. Whitledge, J. C. Kelley, S. A. Huntsman, and R. D. Pillsbury, 1977. Further transition states of the Baja California upwelling ecosystem. *Limnology and Oceanography*, **22**, 264–280.

Washburn, L., and L. Armi, 1988. Observations of frontal instabilities on an upwelling filament. *Journal of Physical Oceanography*, **18**, 1075–1092.

Washburn, L., D. C. Kadko, B. H. Jones, T. Hayward, P. M. Kosro, T. P. Stanton, S. R. Ramp, and T. J. Cowles, 1991. Water mass subduction and the transport of phytoplankton in a coastal upwelling system. *Journal of Geophysical Research*, **96**, 14,927–14,945.

Washburn, L., M. Swenson, J. L. Largier, P. M. Kosro, and S. E. Ramp, 1993. Cross-shelf sediment transport by an anticyclonic eddy off northern California. *Science*, **261**, 1560–1564.

Weatherly, G. L., and P. L. Martin, 1978. On the structure and dynamics of the oceanic bottom boundary layer. *Journal of Physical Oceanography*, **8**, 557–570.

Wiberg, P. L., D. E. Drake, and D. A. Cacchione, 1994. Sediment resuspension and bed armoring during high bottom stress events on the northern California inner continental shelf: measurements and predictions. *Continental Shelf Research*, **14** (10/11), 1191–1221.

Winant, C. D., R. C. Beardsley, and R. E. Davis, 1987. Moored wind, temperature and current observations made during CODE-1 and CODE-2 over the northern California continental shelf and upper slope. *Journal of Geophysical Research*, **92**, 1569–1604.

Winant, C. D., and A. W. Bratkovich, 1981. Temperature and currents on the southern California shelf: A description of the variability. *Journal of Physical Oceanography*, **11**(1), 71–86.

Winant, C. D., C. E. Dorman, C. A. Friehe, and R. C. Beardsley, 1988. The marine layer off northern California: an example of supercritical channel flow. *Journal of Atmospheric Sciences*, **45**, 3588–3605.

Woods, J. D., 1988. Toward a theory of biological-physical interactions in the world ocean. B. J. Rothschild, editor, D. Reidel 650 pp.

Wroblewski, J. S., 1977. A model of phytoplankton plume formation during variable Oregon upwelling. *Journal of Marine Research*, **35**, 357–394.

Zemba, J., and C. A. Friehe, 1987. The marine atmospheric boundary layer jet in the Coastal Ocean Dynamics Experiment. *Journal of Geophysical Research*, **92**(C2), 1489–1496.

Acknowledgements

The hard work of all of the Portland meeting attendees was critical for assembling this report. We also appreciate the effort and care of those who reviewed this document. The support of the National Science Foundation, the Office of Naval Research (Coastal Sciences) and of the National Oceanic and Atmospheric Administration (Coastal Ocean Program) is gratefully acknowledged. Support from all three was administered through National Science Foundation grant OCE92-24824.

Appendix 1: Bottom Boundary Layer Processes

Rapporteur: Chris Sherwood
Participants: Don Boyer, Dave Cacchione, Dave Drake, Burton Jones, Steve Lentz, Chuck Nittrouer, Fred Prahl, Chris Sherwood, Richard Sternberg.

Summary

The working group noted that a significant fraction of all cross-margin transport may occur in the benthic-boundary layer (bbl; the zone spanning approximately 10 m above to 1 m below the sediment–water interface), and that a productive approach for studying this transport is to focus on the processes that generate cross-margin distributions of sediment, biota, and chemical species. In particular, the following fundamental questions were posed:

- How do processes in the bbl influence the spatial and temporal distribution of biologically and chemically important materials?
- How do exchange processes between the bbl and the active sediment layer affect the nature, distribution, and ultimate fate of these materials?

Many bbl processes are forced by processes originating within, or receive input from, other regions, including the nearshore, the surface layer, and the interior. Thus, studies of bbl processes often require measurements in these other regions. By the same token, bbl processes exert influence in these other regions and studies of, for example, circulation or nutrient cycling, can benefit from bbl measurements. For these reasons, bbl studies are important to, and stand to benefit from, a large-scale multidisciplinary study of cross-margin transport.

Research Objectives

The group identified a number of specific research objectives designed to address the fundamental questions listed above. Each of these is discussed briefly below.

Mechanisms for Cross-Margin Transport

The cross-margin (onshore and offshore) transport of biologically and chemically important material occurs through many mechanisms. As discussed in the Geological Oceanography summary, transport of fine particles is particularly important in the movement of trace nutrients, pollutants, biogenic materials, and larvae. Fine-particle transport is controlled by a broad range of physical forcing. Some of the mechanisms that can generate offshore cross-shelf transport are: (a) upwelling relaxation or poleward winds (particularly winter storms) that result in downwelling and net offshore flow near the bottom, (b) impingement of eddies on the shelf that both resuspend and transport sediment, (c) internal waves associated with storm events, (d) Ekman transport beneath the poleward undercurrent, (e) gravity flows, (f) near-bed transport by long waves forced by wave groups, and (g) down-gradient dispersion of material through essentially random fluctuations. Onshore transport can be forced by: (a) upwelling circulation, (b) bedload transport under shoaling waves, (c) baroclinic (estuarine) circulation, and (d) down-gradient dispersion. Many of these cross-shelf transport mechanisms depend on correlations of the fluctuating components of velocity and concentration to produce net transport. These mechanisms are difficult to study because they can produce long-term transport through very short-term fluctuations. (A good analogy is the fair-weather transport of sand onto beaches in the nearshore). Biological and chemical phenomena often play key roles in determining the characteristics and timing of particles supplied to these processes. A major objective of the CoOP studies should be continued investigation of the mechanisms that force cross-shelf transport.

Ekman-Layer Dynamics

Recent work has contributed to the growing realization that Ekman-layer dynamics are substantially modified in the presence of density stratification and a sloping bottom. The resulting asymmetry that occurs between upwelling and downwelling conditions has important implications for transport of material suspended in the bottom Ekman layer. One objective of the cross-margin studies should be to test recent hypotheses of stratified Ekman layer dynamics over a sloping bottom during upwelling and downwelling conditions.

Spatial Scales in the BBL

Little is known about the spatial scales important to bbl dynamics. One objective of bbl research should be to quantify the length scales of spatial variability for current velocities, bottom shear stress, bottom roughness, and benthic communities. This will require mapping bbl features with sufficient resolution to determine wavenumber spectra, correlation length scales, and other measurements of patchiness. It will also require studies to determine the importance of spatial variability to bbl processes.

Recycling and Regeneration of Nutrients

The bbl and bottom sediment are an active reservoir of organic material. Material that is resuspended from the bottom and/or transported in from offshore in the bbl plays an important role in maintaining the high productivity of the coastal zone. The possible role that trace nutrients may play increases the importance of this onshore "conveyor belt." An objective of the CoOP studies should be to examine exchanges between the bbl and the interior and their role in nutrient regeneration and supply of nutrients to the inner shelf and nearshore regions.

Transformation and Fate of Terrigenous Carbon

Some evidence indicates that terrigenous carbon, which is mostly refractory, is transformed into usable forms by bbl processes. Observed cross-margin decreases in the terrigenous carbon were previously attributed to low cross-margin transport rates, but it now appears that some (much?) of the loss may reflect transformation, utilization, and replacement by biogenic carbon. These alternative hypotheses are important to understanding the budget of carbon in ocean margins and should be investigated.

Formation of Sedimentary Strata

Accumulation of sedimentary strata provides a record of physical, geological, biological, and chemical processes and allows us to investigate phenomena on time scales that we cannot observe directly. For example, stratigraphic investigations allow us to study different climates, or measure cumulative effects of very slow processes. On the other hand, process studies in the bbl are necessary to determine how physical, chemical, and biological processes interact to form the sedimentary strata that are ultimately preserved. On the continental margin of the U.S. west coast, rapid uplift has exposed marine sequences in coastal outcrops. This provides geologists with a unique opportunity to study the modern processes via ancient stratigraphic sequences that were

formed in similar environments. The west coast also provides settings where storm deposits (consisting of re-worked marine sediments) and river-flood deposits (consisting of allocthonous terrestrial sediments) both occur and, therefore, is a good location for studying diverse modern processes. An objective of the CoOP research should be further study of the processes that create the stratigraphic record.

Models of Particle Transport

Significant advances have been made toward modeling suspended-sediment transport of mixed particle populations. In particular, recent models describe aggregation processes among particles and the remobilization of material from mixed beds. Testing of these models has been advanced by determining the optical and acoustical responses of mixed-particle suspensions, because these bulk responses are measured in the field by transmissometers and backscatter devices. An objective of CoOP research should be to extend these models to include mixtures of organic and inorganic particulate substances with varying sizes and hydrodynamic properties.

Shelf-Break Processes

Large fish populations are often found near the break between the shelf and slope. The shelf break often marks a transition in zooplankton species composition and is highly productive. Unique bbl processes in this zone include intrusion of the bottom turbid layer into mid-depth waters over the slope, possible breaking of internal waves, and increased importance of gravity-induced processes such as turbidity flows and mass wasting. These bbl processes may act to provide a supply of food particles (plankton and detritus), supporting high secondary production. CoOP studies should provide new data and understanding for this understudied region.

Chemical Transformations and Early Diageneis

Reviewers of this workshop report noted that important chemical processes take place in the bbl that cause chemical transformations and, utlimately, help determine the fates of pollutants, regeneration of nutrients, and early diagenesis of minerals in shelf sediments. CoOP studies should encompass geochemical processes in the bbl, but specific recommendations were not developed during the workshop.

Approaches

The overall approach to studying the bbl should be an iteration among hypotheses, models (conceptual, numerical, and physical) and field observations. New technology is now available that can be fruitfully employed in bbl studies. Many of the following measurement strategies rely on new devices and support that only can be provided in the context of a large, multidisciplinary program.

Cross- and alongshelf arrays and moorings are required to measure spatially varying bbl processes. Moorings and tripods should be deployed to support long-term sampling devices and to provide closely spaced vertical measurements tying bbl processes into mid-depth and surface phenomena.

Rapid profiling devices and towed packages allow spatial surveys of currents and water properties (including temperature, salinity, light levels), and concentrations of suspended sediments, photosynthetically active pigments, and many chemical constituents including dissolved oxygen, nutrients, and trace metals. Many profiling instruments are now designed to be lowered all the way to the sea bed, providing data in the relatively thin bbl.

Bio-acoustics now allow better resolution and characterization of mid-depth scatterers. Bottom-mounted acoustic backscattering devices are proving useful for measuring particulate concentrations, both high up in the bbl and very near the bottom. These devices now allow long time series or large spatial surveys of nearly continuous vertical resolution.

A wide range of sensors are now available for use on profiling and bottom-mounted instruments. Combinations of sensors (e.g., transmissometers and fluorometer, or optical and acoustic backscatter devices) now allow better identification of suspended particles. Bio-chemical sensors are becoming available that will allow even better determination of particle composition. Laser diffractometers, CCD cameras, and digital image processing are providing valuable data on the size distribution of suspended particles. These sensors should be used on moorings, towed packages, and bottom tripods to determine the nature of particulate materials transported across the shelf.

Recently, techniques for detailed stratigraphic characterization have been used to evaluate changes in grain size and bedding caused by benthic faunal activity and short-term deposition events. These techniques should be coupled with process mea-

surements to help researchers connect sedimentary processes, particularly events, with the resulting stratigraphic record.

Only a few devices are available that make in situ measurements of suspended and bottom sediment properties. Further development, testing, and deployment of these devices should be part of the CoOP program, because it is often impossible to recover samples without affecting their properties.

Event-controlled sampling strategies allow unattended devices mounted on moorings or bottom tripods to take samples at the most useful times. These sampling devices should be deployed to obtain "ground truth" data of suspended particulates to calibrate proxy measurements from optical and acoustical instruments.

Appendix 2: Inner Shelf Processes

Rapporteur: Barbara Hickey
Participants: John Allen, Hal Batchelder, Dave Cacchione, Richard Dewey, Scott Dinnel, Dave Drake, Steve Gaines, Barbara Hickey, Steve Lentz, Steve Lindley, Bruce Menge, Mark Merrifield, Ken Parker, Bill Peterson, Ron Schlitz, Ted Strub, Catherine Woody.

Introduction

The inner shelf is generally defined as the region where the surface and bottom boundary layers of the coastal ocean interact, realizing that the outer edge of this region is extremely time- and space-dependent. A broad, "working" definition includes regions just inshore of the generally well observed (if not well understood) midshelf region through the surf zone and intertidal regions. Other definitions, based for example on sedimentary properties, might differ. In this report we emphasize the region extending from just inshore of the midshelf region (30–60 m water depth) to the outer margin of the surf zone (typically 3 m water depth) but include the intertidal zone. The surf zone was excluded for two reasons: first, the physical dynamics of the surf zone region are potentially dominated by different physics (breaking wave dynamics versus wind-driven or buoyancy-driven flow); and second, investigation of surf zone physics, optics, and biology requires different technological and logistical considerations than regions that are not subject to breaking waves.

The inner shelf is home to diverse biological communities, including many species of commercial importance. These nearshore species commonly have planktonic larval stages whose fate is partially set by the pattern of transport. The inner shelf is also crucial to the dynamics of nutrients and trace elements that play important roles in coastal productivity. Despite its profound importance, the inner shelf is the least studied portion of the coastal ocean. Studies of the inner shelf are rare because it has been a logistically difficult place to work. Intense wave action makes maintenance of moored arrays of equipment extremely difficult. Instrument failure is frequent and repair is both difficult and hazardous. Most ships from the UNOLS fleet cannot (or will not) work in such shallow water, or, if they can, are not properly equipped to make

the required measurements. Thus, ignorance of the transport and retention processes in shallow water represents a serious gap in our knowledge of the coastal ocean.

Technological advances in ocean instrumentation, such as shipboard and moored Doppler current meters and moored bio-optical and chemical sensors make work over the inner shelf more feasible today than ever before. CoOP should give high priority to studies which increase our understanding in this important region. Since so little is presently known, the system must be addressed as a whole. Specifically, we ask:

> What are the processes which regulate transport, transformation, and retention across and within the inner shelf?

Background

Spatially and/or temporally limited circulation data over the inner shelf are available from Washington (Hickey, 1989), northern California (Winant *et al.*, 1987), southern California (Winant and Bratkovitch, 1981; Lentz and Winant, 1986; Hickey, 1992) and from the very broad shelf of the southeastern U.S. (Blanton, 1981; Pomeroy *et al.*, 1993). The bottom topography along the U.S. west coast varies dramatically with latitude: the Washington shelf is relatively broader (~40 km); the shelf off northern California is narrow (~20 km); and the shelf off southern California is very narrow (~5 km). Data from these prior studies may provide some of the background information necessary to design a comprehensive field study of inner shelf physical circulation, biology, chemistry, and geology. The one common conclusion from the inner shelf experiments to date is that the alongshore currents are reduced in amplitude relative to those at midshelf. The circulation experiments off Washington also provided a simultaneous and detailed description of upwelling, nutrient uptake and regeneration, and phytoplankton growth rates over several upwelling and downwelling events in the Pacific Northwest (Hermann *et al.*, 1989). The relationship between the circulation, and biological and chemical processes has been more thoroughly addressed for the wide inner shelf of the southeastern U.S. (e.g., Pomeroy *et al.*, 1993).

The physical environment over the inner shelf is significantly different from that farther offshore, since, by definition the wind-driven surface layer and the bottom frictional layers are no longer distinct over the inner shelf. Over the midshelf, these layers are separated by an interior region in which frictional effects are minimal. The

structure of the wind field over the inner shelf may be more strongly affected by local orographic effects caused by coastal mountains and headlands than the region farther offshore. The effects of land–sea temperature differences are also felt more strongly over the inner shelf. Spatial differences in characteristics of the sea bed such as roughness length, existence of sand waves, etc., may cause differences in bottom stress, and therefore, in details of the cross-shelf flow in the boundary layer. Shoaling waves are likely to cause enhanced vertical mixing over the inner shelf. Also, the interaction of waves around topographic features can dramatically affect local transport processes.

Since upwelling occurs over the inner shelf, the front generated by the upwelling process exists over the inner shelf for at least some portion of its lifetime and may move offshore and back onshore in response to variations in the wind. Models suggest that during downwelling, a front may effectively separate inner shelf waters from midshelf waters (J. Allen, personal communication). Fronts may also be formed on the inner shelf by the enhanced wave mixing and tidal processes. These fronts and the change in stratification across the inner shelf will change the spatial structure and propagation speed of internal waves and tides. In the region within and directly adjacent to the surf zone, breaking waves lead to processes such as edge waves and rip currents. Although such processes can be indirectly regulated by wind forcing, they generally have time scales an order of magnitude less than that of the majority of the directly wind- or buoyancy-driven transport processes (minutes to hours). Finally, we note that the inner shelf feels the three-dimensional effects of relatively small scale ($\sim$10 km) headlands or bays.

The merging of the bottom boundary and surface boundary Ekman layers over the inner shelf may affect the chemistry and biology of this zone. Physical transport directly affects the spatial and temporal distribution of nutrients, trace metals, particulates and marine organisms. Enhanced mixing will affect the availability of prey to predators (Rothschild and Osborn, 1988). At times, suspended solids concentrations will be markedly higher in the photic zone of the inner shelf than farther offshore because of the direct connection between the bottom and the surface. Reduced water clarity may affect total production and/or species composition of the phytoplankton. The higher suspended inorganic solids might also adversely affect feeding behavior, reduce growth rates and affect survival of zooplankton in the inner shelf region.

Proposed Research

To improve our understanding of transport, retention and transformation processes over the inner shelf, several questions have been identified as having the highest priority.

Transport Processes

1. Are transport processes over the inner shelf fundamentally different from those over the midshelf?

   Within the inner shelf, boundary layers (i.e., meteorological, upper ocean, bottom and sedimentary interfaces) interact directly and ultimately may become indistinguishable. This interaction may alter the relative importance of transport processes within any one of the layers, and clearly provides communication pathways for vertical and horizontal material flux. At the offshore (deeper) limit of the inner shelf, these boundary layers do become distinguishable and interact more independently with the flows and processes over the mid- and outer shelf.

   Circulation processes over the inner shelf itself are expected to be frictionally dominated, but the transition region between the frictionless interior and the frictional inner shelf is not well understood. Most models have employed a wall at the seaward edge of the inner shelf and simply ignored it, since net transport into the inner shelf is assumed small (e.g., Mitchum and Clarke, 1986). This assumption, has recently been verified by observations off northern California (Lentz, 1992). Moreover, limited rates of net transport across this boundary do not mean that they are biologically or chemically unimportant, since cross shelf currents at any particular depth can be significant even when the net (or vertically averaged) transport may be near zero. The depth at which the quasi-frictionless interior flow disappears must be a complicated function of the wind forcing, bottom roughness, stratification, bottom slope and the three-dimensional circulation, each of which varies spatially. The transition may be smooth or may occur abruptly across a front. For example, the water column inshore of the front may be completely mixed, whereas that offshore of the front may be strongly stratified.

   The transport processes over the inner shelf are likely to also be a function of bottom topography, even in a quasi- two dimensional area. Off Washington, where the inner shelf is wide in comparison with the horizontal extent of direct

upwelling, the upwelling front is often confined to the inner shelf. Off California, on the other hand, the upwelling front moves rapidly offshore of the inner shelf, and so the inner shelf may be more well mixed. These differences would lead to dramatic spatial differences in cross shelf circulation patterns and to lateral mixing processes as well as to net cross shelf transport.

2. How are the structure of the local wind field and the atmospheric boundary layer affected by the coastline, and how do these affect transport processes on the inner shelf?

   Observations suggest that spatial scales of wind variability in the range of 0–20 km are determined by the coastal topography/morphology (coastal headlands or coastal mountain ranges). In an experiment off northern California, significant small scale variations were found in the vicinity of Point Arena (Zemba and Friehe, 1987; Dorman, 1985). Similar spatial disturbances are expected in the lee of smaller features (~10 km). Temporal variability of the wind field, on the other hand, is controlled by the larger scale atmospheric systems — synoptic, mesoscale, and diurnal.

   Alongshore variability in the strength and direction of the wind over the inner shelf might be important in the creation of localized nearshore regions where zooplankton and larval stages are retained, or may provide significant transport opposing the seasonal mean transport farther offshore. For example, very variable and weak northward winds over the inner shelf of the mid-Atlantic Bight have been proposed (and modelled) as a mechanism for retaining blue crab larvae near the mouth of the Chesapeake Bay (Johnson *et al.*, 1984). Without this nearshore northward transport, after export from the estuary the larvae would be swept south in the alongshore drift during their 30 day larval period. On the west coast, with its generally narrower continental margin, any such return flow will likely be much more confined to the coast and controlled by orographically steered local winds.

Retention Processes

1. Are transport processes over the inner shelf fundamentally two-dimensional or three-dimensional?

Some models of cross-shelf circulation with uniform coastline and wind forcing depict a two-dimensional circulation pattern. Wind-driven currents exit to (enter from) the offshore region in a relatively shallow surface layer during upwelling (downwelling) periods. Water returns in a more diffuse interior circulation pattern that is intensified near the bed as upwelling proceeds. It is unknown whether this circulation pattern exists on the inner shelf because few measurements have been made in this region.

Major headlands cause significant modifications in the large-scale circulation. In spring and summer, a southward flowing jet is thought to be deflected offshore as it encounters major capes, although the dynamics governing this process are not certain (see the Frontal Processes Report, Appendix 5). This offshore deflection is hypothesized to transport large (3–6 Sv) quantities of water and other passive substances. Moreover, gyres may form behind such headlands and serve as retention centers. For example, on the southern side of Pt. Reyes, fine grained sediments are found in shallow water at depths that usually have only coarser sand. Similar features (gyres, eddies) may occur at smaller scales, when a coastal jet interacts with less prominent headlands or bottom topography, creating small-scale alongshore variability in cross-shelf transport patterns on the mid- and inner shelf that is strongly linked to topographic features.

There is some indirect evidence that strongly three-dimensional circulation patterns are typical on the inner shelf. For example, inner shelf habitats often demonstrate a large degree of biological variation. Large differences in abundance, recruitment, and growth rates of benthic invertebrates occur which appear related to differences in nearshore productivity, nutrients, and onshore transport. However, the extent to which these differences reflect mesoscale or macroscale variation in topography, currents, and winds is unknown.

2. Is the inner shelf a particle/organism trap?

A fundamental problem in the coastal zone is how the planktonic stages of nearshore adult species are able to affect life-cycle closure within the coastal zone. The question is: "How do these organisms avoid offshore transport or accomplish compensating onshore transport?"

Examples that organisms do accomplish this abound. Within the holoplankton, a number of species maintain the centers of their population abundance within the

nearshore (Peterson *et al.*, 1979). Within the meroplankton, adult populations that live benthically in the subtidal or intertidal, have planktonic stages with durations from days to months. Dungeness crab larvae spend 6 months within the plankton, subject to offshore transport, after which they must recruit to the adult benthic environment within the 30 m isobath. Similarly, other species, such as barnacles, mussels, and urchins, have shorter planktonic stages ($\sim$ days to weeks), but still must recruit to substrates within the intertidal or near subtidal, or be lost permanently from the population.

Organisms can take positive action to affect their probability of return to adult habitats nearshore. For example, with Dungeness crab, spawning occurs during winter when the nearshore transport is onshore, and strongly alongshore. In other species, ontogenetic or diel vertical migration in the presence of both alongshore and cross-shore vertical shear may permit planktonic larval stages to remain near suitable adult habitat. None of these mechanisms, however, is always effective. Hence the successful recruitment of larvae is extremely variable over space and time. Much of this variability may have its source in the vagaries of nearshore transport (e.g., Roughgarden *et al.*, 1988; McConnaughey *et al.*, 1992).

Transformation Processes

1. What are the relative importance of various transport pathways into, within, and out of the euphotic zone?

   The inner shelf region provides the most direct pathway for infusing near-bottom material (i.e., trace metals, nutrients) into the surface euphotic zone. Turbulent mixing and the vertical flux of material within the inner shelf are both important processes related to transport and transformation of nutrients, marine organisms, momentum, mass, and particulates. Boundary layer forcing (i.e., surface and bottom stress) may dominate the vertical flux as the water depth diminishes and the boundary layers directly exchange material. The temporal variation of inner shelf mixing (both lateral and vertical) is currently unknown. For example, what is the relationship of mixing processes to upwelling/downwelling events?

2. Are trace metals important contributors to variability in primary production?

   Biological rate processes reach maximum values on upwelling coasts but exhibit high variability even when macronutrients (N, P, Si) are abundant. New evidence

from the open ocean suggests that trace metals such as Fe may be in short supply and can profoundly affect rate processes, community composition, and ecosystem function.

The inner shelf is likely an important source of trace metals to the coastal ocean because the majority of trace elements in that region likely came from bottom sediments. These elements diffuse upward from the sediments into the bottom boundary layer where they are subsequently moved across the shelf and diffused or advected vertically into upper portions of the water column. The transfer of trace elements from the inner shelf sediments into the water column is likely enhanced over the inner shelf where the surface and bottom boundary layers meet. Mechanisms of trace metal supply to the shelf may be substantially different than mechanisms of macronutrient supply because of the different source depths. The biological/chemical processes important in transfer/transformation of trace metals within and across the inner shelf are presently unknown. The processes of complexation with organics/sediments in suspension and of biological uptake and advection may be of special importance, but are poorly known.

Implementation

The overall goal of a study of the inner shelf is to determine the spatial and temporal variability in transport, retention and transformation processes, with particular attention focused on the questions stated above. Because the actual processes (not just the relative amplitudes of specific processes) are so strongly dependent upon topography, we believe that three types of topography should be studied comparatively. The three topographic regimes are: (1) straight coast (long beach); (2) bumpy coast (scalloped headland and cove, ~10–20 km alongshore scale); and (3) extreme (cape, 100 km scale) (see Figures 2a,b,c).

Measurements should be obtained on two time frameworks: (1) high horizontal resolution measurements made during shorter (1–4 week) periods capable of resolving synoptic, mesoscale, and diurnal time scales; (2) coarser scale fixed point (moored or coastal) stations maintained for several months.

A strawman proposed structure for the moored buoys consists of moorings at distances of 1, 4, 7, and 10 km offshore. The moorings would include surface meteorological measurements as well as subsurface measurements, including currents, opti-

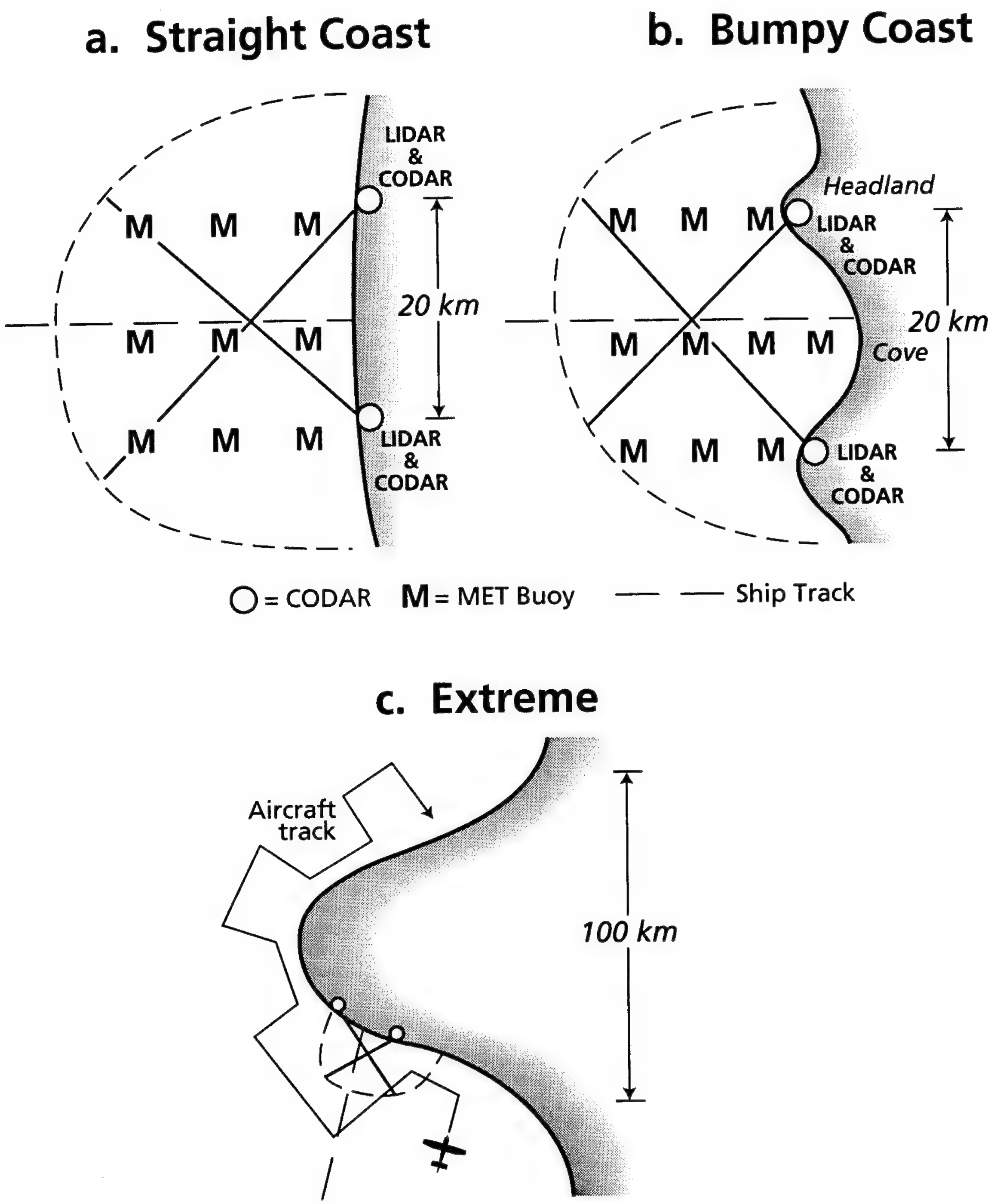


Figure 2: Schematics of three possible inner shelf studies: straight coast, small promontories and with a large promontory. The solid lines and short dashed lines suggest the range of a shore-based radar current measurement system.

cal/acoustic sensors, nutrients, settling plates and fluorometers. Off the straight coast, there should be at least two and preferably three lines separated by about 10 km. Off the headland and cove region, with headlands separated by 20 km, there would be three lines, one at each headland and one off the cove in between. In the area of the large cape (100 km), the array may be different in scale. Three lines would extend 10–20 km offshore on the southern side of the cape, where an upwelling center is expected in the ocean and a region of supercritical flow is expected in the wind field. Surface variables measured at each meteorological buoy would include wind speed and direction, surface temperature, air temperature and humidity, and atmospheric pressure. The location of the mooring and the surface data would be telemetered in real time to alert investigators to movement of the moorings and aid in real time deployment of surveys, in response to wind and oceanographic events, as revealed by the meteorological and surface temperature fields. This array would be supplemented by two or three additional current meter moorings along each line to adequately resolve the current structure. At least at the sites that include meteorological sensors, transport in the surface and bottom boundary layers should be adequately resolved.

Before final design of the moored array, surveys should be conducted to oversample the field and determine the most reasonable sampling strategy. The methods of performing these surveys (LIDAR, aircraft, ADCP/CTD...) need to be carefully determined. Winter and summer (downwelling/upwelling) conditions would likely demand different mooring locations.

The difficulty of maintaining moored instrumentation in shallow water will require different methods than are typically used in deeper depths over the shelf. In particular, it is likely that some instrumentation will need to be "jetted in" (driven into the bottom). Bottom mounted Dopplers may be particularly useful for some applications.

During short, intensive surveys, measurements of wind fields, and surface currents would be made at high horizontal resolution using shore-based remote sensing techniques. Dual frequency Doppler LIDAR measurements from two alongshore coastal sites can determine the two-dimensional fields of surface winds (with some vertical structure) with 0.5 km horizontal resolution, to a distance of 10–20 km offshore during clear weather. Similarly, dual frequency radar can estimate three-dimensional wind speeds, at least during periods of precipitation. Thus a region 10–20 km square around each met buoy array could be sampled continuously for one or more 1–4 week periods.

At the same time as the LIDAR/radar wind surveys (the intensive surveys), a small vessel would cover a cross-shelf transect between 0–20 km, releasing radiosonde balloons to determine vertical profiles of temperature and wind within the marine boundary layer (MBL). This would be done every six hours, allowing a description of the temporal variability of the MBL in the offshore direction during the various larger-scale wind regimes.

A second ship would perform shipboard Doppler/CTD/ fluorometer, surveys and obtain nutrient, trace metal, phytoplankton and zooplankton samples. High spatial resolution fields of surface currents would be obtained using Doppler radar (OSCR, Coastal Ocean Dynamics Application Radar – CODAR,...) from the same two sites as the LIDAR, over the same period. This would resolve the two-dimensional structure of the currents and regions of divergence (upwelling) and convergence (downwelling) and the response to local wind forcing (stress and curl of stress).

The measurements in the cape region could employ one or more aircraft to cover the larger coastal region north (upstream) and south of the cape. This would also resolve the structure of the MBL.

During the shipboard surveys, the inner shelf could be seeded with density-following Lagrangian GPS drifters. These would help elucidate the extent to which the inner shelf is a particle trap. Fronts over the inner shelf would also be seeded to help elucidate lateral mixing processes. Seeding would be done on an event-based response basis.

It is important to include wintertime studies over the inner shelf as well as summertime studies, which tend to be overemphasized by past measurements. Winter is especially important for aspects of larval retention and sediment transport. It is already clear from modeling studies (J. Allen, personal communication) and from observational results (Lentz and Trowbridge, 1991) that upwelling and downwelling processes are not symmetrical. The increased depth of mixing and rate of mixing during winter storms in the Pacific Northwest is likely to demonstrate dramatic differences in transport and retention processes from summertime upwelling regimes.

Modeling

Modeling must be considered as an integral part of the experimental design, implementation and analysis for the inner shelf. Three interrelated models are envisioned as being important: biological/ecosystem models, circulation/diffusion models, and sediment suspension and transport models. Each of these efforts should help guide the observational programs, and the possibility of data assimilation should be encouraged.

Appendix 3: Upper Ocean Processes

Rapporteur: Larry Small
Participants: Mary Batteen, Ken Bruland, Dave Checkley, Patrick Gallacher, Paul Martin, Jeff Paduan, Don Redalje, Richard Rotunno, Larry Small.

Introduction

In the strongly wind-driven systems along the western margins of the world's continents, the primary producers are generally medium-to-large-sized phytoplankton cells, with chainforming diatoms usually the predominant taxa (Margalef, 1978; Biasco *et al.*, 1981). This is true for the strongly wind-driven system off the U.S. west coast (Hood, 1990). It is generally assumed that in order to grow vigorously, large chain-forming diatoms require an upwelling circulation to both maintain themselves within the euphotic zone and to be resupplied more or less continually with ample nutrients. However, the basic upwelling circulation off the U.S. west coast has a strong equatorward component and a measurable offshore component in upper waters, which tends to move diatom communities strongly southward and offshore. In addition, during intermittent periods of wind reversal, other phytoplanktonic communities besides diatom-dominated ones often emerge (Hood, 1990), so that attention must be paid to community taxa shifts as well as spatial dynamics of diatoms alone. Finally, the extensive blooms of chain-forming diatoms common to wind-driven coastal systems can undergo mass flocculation and sedimentation if nutrient limitation approaches during calm periods or wind reversals. Blooms might sediment rapidly before extensive consumption by zooplankton, carrying both vegetative cells and resting states to the sediments (Berger, 1976). Bloom aggregation might be seen as a part of diatom life-history adaptations and may serve to retain diatoms nearshore (Alldredge and Gotschalk, 1989). Moreover, when it occurs it results in a decoupling of grazing from phytoplankton production processes since primary producers are lost to the system before extensive grazing is possible.

In regions of smooth coastal topography and bathymetry, the coastal jet parallels the topographic/bathymetric contours, and appears to act as a near-surface barrier to seaward extension of upwelling-induced phytoplankton blooms (Small and Menzies, 1981; Hood, 1990). As a result, intense concentrations of phytoplankton pigments, often stretched meridionally into a near-surface band or bands, are noted within, or

just shoreward of, the core of the jet. The sharp frontal structure established by the jet also can create strong nutrient fronts, which help sustain the vigorous diatom growth there (Traganza *et al.*, 1987). In regions where the coastal jet meanders well offshore (usually in the proximity of major topographical features such as headlands on capes), the area influenced by upwelling often extends well offshore (Hood, 1990). Near-surface phytoplankton stocks (mainly diatoms) are often entrained as long seaward-extending filaments under these conditions. As the basic phytoplankton communities recur year after year in the same general near-coast regions, there must be mechanisms to retain seed stock in those regions. Suggested mechanisms include (1) return of seed stock via mid-depth and/or near-bottom poleward and onshore transport; (2) advection from the north; (3) growth during upwelling relaxation events and/or during the non-upwelling season; (4) entrainment in the coastal jet as it meanders close to the coast from offshore; (5) rapid sedimentation of some blooms nearshore followed by later upwelling of resting stages; or (6) some combination of the above.

Upwelling relaxation events, sometimes of many days duration, occur during upwelling season when equatorward winds subside or change to poleward direction (Halpern, 1974; Walsh *et al.*, 1977; Small and Menzies, 1981; Hermann *et al.*, 1989). Upper water circulation responds rapidly to these wind changes, and gross redistribution of phytoplankton properties occur. Only when strong upwelling-favorable winds return do these properties re-align into "typical" upwelling patterns. Thus, under intermittent upwelling and non-upwelling conditions, there appears to be strong advective–diffusive control of, for example, cross-margin chlorophyll distributions, while under persistent upwelling the distributional patterns of chlorophyll also tend to persist, and any changes are mainly due to phytoplankton growth and death (Small and Menzies, 1981; Hermann *et al.*, 1989).

In all of these basic patterns, the role of bacteria and the microbial loop has not been adequately addressed to date, and needs to be done.

Fundamental Question

Given the above background on upper water-column dynamics in the wind-driven system along the western margins of the U.S., we can pose two fundamental questions:

1. What physical, chemical and biological processes control the production, distribution and ultimate fate of phytoplankton (with particular reference to blooms of large diatoms) in the upper water column under the strongly wind-driven circulation off the U.S. west coast?
2. Are bacterial dynamics (microbial loop processes) significant under the strongly wind-driven circulation off the U.S. west coast, and if so, under what conditions?

These remain significant questions. Upwelling areas ultimately yield the greatest harvest of fish in the ocean, and it has always been presumed that the luxuriant diatom production ultimately undergirds this large production of fish biomass; however, the effects of microbial populations have never been clearly elucidated. Off the U.S. west coast the commercial fisheries north of Cape Mendocino are generally dominated by hake, salmon, rockfishes, and several flatfishes. To the south a number of pelagic species, most notably mackeral and squid, are important as well.

Ancillary Questions

Under the main questions are a hierarchy of ancillary questions which need to be addressed under CoOP:

1. What are the space and time relations between the onset of upwelling and the subsequent development of a phytoplankton bloom?
   (a) To what extent do physical dynamics (e.g., coupled upwelling–downwelling structure) within an upwelling event impact the distribution of properties and phytoplankton and microbial processes?
   (b) To what extent do the magnitude and duration of the relaxation between upwelling events determine the distribution of properties for subsequent upwelling bloom events?
   (c) What is the relative importance of diatoms, other phytoplankton, and bacteria during periods of upwelling and relaxation of upwelling?
   (d) What is the relative importance of benthic and atmospheric deposition processes over the shelf in contributing nutrients (both traditional nutrients and trace elements) towards the development of diatom blooms compared to upwelled nutrients from offshore sources?

(e) As the concentrations of dissolved trace metals (e.g., Fe, Mn, Zn, Co, Cu) are all elevated at the ocean margins, to what extent are these trace metals necessary for the development and maintenance of blooms of large diatoms?

(f) What are the important physical–chemical tracers of upwelling that are independent of the biologically active tracers?

2. Are there cross-margin gradients in biomass and in new and regenerated fractions of total primary production over all scales of upwelling?

   (a) Are there significant changes in phytotaxa with changes in primary biomass or with changes in the fraction of total production that is new production?

   (b) As cross-margin transport occurs, how do the assimilation, remineralization, and scavenging rates of biologically significant trace metals affect their biological availability? Do any of these trace metal nutrients reach biolimiting concentrations for the production of large diatoms and thus have an effect on the taxonomic composition of phytoplankton?

   (c) Is there a commensurate cross-margin gradient of physical properties? Is there a dynamical explanation (e.g., can the rate of offshore advection explain the observed gradients)?

3. To what degree can the space/time variability of diatom biomass be explained by the space/time variability of grazing by macrozooplankton or variability in mass aggregation, and to what degree can that variability be explained by space/time variability in physical processes (such as surface convergence, for example).

4. To what degree does microzooplankton grazing on bacteria and very small, non-diatom phytoplankton affect the relative abundance of larger diatoms during upwelling and relaxation of upwelling?

5. How are the population dynamics of phytoplankton cells affected by their occurrence in microlayers which develop in the photic zone of the wind-driven coastal margin?

   (a) To what extent do these microlayers serve as loci of grazing activity?

   (b) To what extent are nutrients assimilated and remineralized in these microlayers?

(c) What are the physical processes (e.g., vertical shear and stability) that critically affect the generation and maintenance of microlayers of cells? How are these layers affected by surface fluxes of momentum and heat?

6. What role does subduction play in cross-margin transport, and if so, can this explain replenishment of seed stock over the margin?

   (a) Is subduction of the upwelled water at the coastal jet non-hydrostatic; e.g., are there significant time-dependent vertical velocities?

   (b) Are the subducted water and contained materials forced under the jet?

   (c) Are the subducted water and contained materials entrained into the jet and advected along the coast?

   (d) Is there any significant return flow of subducted water and contained materials?

One might also consider that upper-ocean processes in these wind-driven coastal systems would involve important questions about the air–sea interface and atmospheric deposition, and their relation to biological productivity:

1. What is the role of phytoplankton blooms in the consumption/production and air–sea exchange of biogenic gases and other significant chemical entities?

   (a) To what extent do the coastal margins serve as sources or sinks for radiatively important gases?

   (b) To what extent is the atmosphere a source of important elements to phytoplankton, and is phytoplankton a source of materials that modify atmospheric conditions?

2. What is the interaction between the atmospheric and oceanic boundary layers during upwelling, and how does this interaction affect primary production?

   (a) Can the position of the core of maximum phytoplankton biomass and productivity in the zonal direction be directly related to the curl of the wind; i.e., as cold, upwelled water continues to stabilize the atmospheric boundary layer from the shore outward, thus continuing to reduce the wind stress

from the shore outward, does the spatial gradient of stress (resulting in a positive curl) continue to move seaward and accelerate the propagation of the front, thus setting the position of the core of maximum phytoplankton biomass and productivity?

(b) Does upwelling-induced fog near the coast help create the phase lag between the onset of upwelling and the creation of the maximum diatom blooms further seaward?

(c) Can the observed alongshore variability in upwelling intensity be explained by similar-scale variability in wind stress?

Approaches and Implementation

It is anticipated that the above biological, chemical, and physical questions and sub-questions will be addressed using several different approaches. Clearly many traditional biological and chemical techniques have been too slow in the past to allow build-up of statistically sound data sets in the time-space scales dictated by the atmospheric and hydrographic forcings in strongly wind-driven regions. One approach thus could be to utilize as core measurements only those measurements that can easily be done using rapid profiling techniques, instrumented buoys and drifters, and satellite or aircraft instrumentation. Phytoplankton fluorescence and light absorbance in several wavebands can now be rapidly done, both in macro- and micro-scale, by profiling techniques, for example. Macro-scale pigment absorbance and fluorescence data can also be logged from buoys and drifters, and from satellites and aircraft for broad-scale mapping of surface patterns. Fluorescence measurements are already well-known to the scientific community. Direct measurements of chlorophyll absorbance are now possible as well (R. Zaneveld, personal communication). Recently, flow injection/chemiluminescence techniques have been, or will soon be, developed for measurement of trace metals such as dissolved and particulate Fe, Mn, Co and Cu (Sakamoto-Arnold and Johnson, 1987; Coale *et al.*, 1991; Chapin *et al.*, 1991; K. Johnson, personal communication), to go along with continuous in situ determination of major nutrients such as nitrate (Johnson *et al.*, 1990). Bio-optical techniques afford rapidly-obtained measurements which might act as good surrogates for certain biological measures (Dickey *et al.*, 1991); for example, photosynthetic carbon uptake rate, traditionally done by time-consuming C-14 techniques, might be estimated rapidly as the product of irradiance flux, the coefficient of

light absorption by phytoplankton, and the quantum yield of photosynthesis (Bannister, 1974; Kiefer and Mitchell, 1983). Irradiance flux is easily and quickly measured, and the newly developed absorption meters promise to deliver rapid and precise measures of absorbance by phytoplankton through the photic zone. Quantum efficiency of photosynthesis is not constant, and in fact is at least a function of irradiance, but it is reasonable to assume that decent values can be arrived at. Marra *et al.* (1993) found that the above bio-optical model explained 90% of the variance of C-14 productivity in the Gulf of Maine, suggesting that use in strongly wind-driven systems should be explored. "Ground truthing" by traditional C-14 techniques would presumably be done as needed.

Some biological/chemical measurements do not yet lend themselves to rapid analysis, and yet need to be done. Chemical tracers of particle residence times and scavenging, such as Th-234, require water-bottle collections using very clean techniques, for example. Recently developed optical-electronic means to assay zooplankton size groups in-situ promise to yield quicker and better biomass information, although rapid grazing rate information is still not possible. Gut evacuation rate data on zooplankton size groups (commensurate with biomass size groups) may be an approach to consider. Particulate organic carbon and nitrogen, dissolved organics, and any species identification still require water-bottle collection and subsequent chemical or microscopic analysis in the lab. Perhaps some optical, sonic, or electronic measurements will yet be developed as adequate surrogates for some of the currently hard-to-measure attributes. Until that time, however, less temporal-spatial coverage for these measurements will have to be accepted.

Modeling

Ultimately the goal must be to integrate a model (or models) of phytoplankton (diatom) growth, and concomitant removal by grazing and sinking, with a physical model (or models) addressing three-dimensional advection, convergence, diffusion and mixing. The Wroblewski (1977) and Jamart *et al.* (1977) models would provide a good start. Furthermore, a coupled mesoscale ocean–atmosphere model will ultimately be necessary to study the intense interactions and potentially strong feedbacks that occur during strong upwelling and wind events. In upper waters, a mooring and drifter program adequate to delineate meteorological and physical oceanographic processes

will be sufficient to yield the biological terms in any model (or models), providing the appropriate biological/chemical/optical sensors are part of each mooring and drifter array.

Appendix 4: Interior Water Column Processes

Rapporteur: Ken Brink
Participants: Ken Brink, Ken Johnson, Mike Kosro, Mike Mullin, William Neff, Terri Paluszkiewicz, Fred Prahl, Larry Small, Libe Washburn, Roland Wollast, and Xiuzhang Zhang.

1. Introduction

The interior of the water column is taken to be the region away from the surface and bottom turbulent layers and away from frontal regions. The interior is expected to be volumetrically the largest portion of the shelf waters, is generally the pathway by which upwelling source waters approach the coast, and it may play an analogous role during downwelling conditions. The interior is a location where important biological and chemical processes take place. For example, while phytoplankton concentrations are likely to be largest near the surface, both phytoplankton and zooplankton in the interior may well be important to the overall system dynamics. In sum, the interior is both a location for major transformations in its own right, and it is a conduit for waters to and from other important shelf subregions.

The working group quickly concluded that much of the interior's importance lies in its interactions with other boundary layer regions and with offshore waters. For this reason, much of the following discussion relates closely to the findings of other working groups. The reader should note, too, that not all disciplines were equally represented in the working group sessions: undoubtedly some important gaps remain in the following results.

2. The Question

> What are the processes representing biological, chemical, geological and physical pathways between interior shelf waters and the surface and bottom turbulent boundary layers and what are their relative importance?

Specifically, the group felt that the following processes were particularly worthy of attention.

- Upwelling: The traditional concept of upwelling calls for waters near the coast to be cooled due to wind-induced inner shelf vertical transport. In this idealization, alongshore winds are taken to be uniform in space, causing an offshore surface Ekman transport extending far offshore. This concept has stood the test of time well, but there is a striking lack of direct measurements of the associated vertical transports. Over the last decade, new ideas (for example, micronutrient limitation of growth) and new observational tools (such as Seasoar and moored nutrient sensors) have made the basic problem worth revisiting. Since upwelling is known to be a major channel for delivery of nutrients to the euphotic zone, the fundamental importance of the issue remains.

- Downwelling: When winds off the west coast are poleward (primarily during winter conditions), surface waters are transported toward the shore and forced downward. Recent modeling studies (J. Allen, personal communication) have emphasized that this process does not appear to represent the simple reverse of upwelling. Nearshore fronts and peculiar bottom layer dynamics seem to become important as the process advances, but we do not know the role played by interior waters under these conditions. Downwelling removes phytoplankton from the euphotic zone, and provides a biogenic particle flux to deeper layers, but the full implications of the process have never been studied. Downwelling might represent a major sink for production, and act to condition waters (in terms of nutrient supplies and harboring seed phytoplankton stocks) prior to subsequent upwelling events.

- Spatial Variability of the Surface Wind Stress: Traditional ideas about upwelling and downwelling have it that winds are uniform in space, and vertical motions are largely confined to near the coast and the upwelling front. Observations have consistently shown, however, that alongshore winds over the shelf are not uniform across the shelf. The resulting wind stress curl should thus drive vertical motions (both upward and downward) that imply mid- to outer shelf secondary sources and sinks to the euphotic zone distributed across the continental margin. Past studies (e.g., Winant *et al.*, 1988) have shown that areas with irregular coastal orography and topography are particularly subject to these stress variations. While dynamical models argue for the importance of the cross-shelf stress distribution in shaping current structures, the biological, chemical and geological implications of these transports are unknown and largely unstudied to date.

- Subduction: Subduction at water mass boundaries may represent an important pathway that removes phytoplankton, particles and dissolved chemical species from the euphotic zone. The occurrence of these subducted water masses is not well documented over the shelf and slope, although there is suggestive evidence (e.g., Stevenson *et al.*, 1974). As a result, we have little knowledge of their volume, vertical velocities, spatial distribution or frequency. Characterization of the physiological state and taxonomy of phytoplankton is also poorly defined. However, these are important issues since phytoplankton input via subduction may represent a significant food source for zooplankton and may be a stock source for subsequent seeding of the euphotic zone through upwelling.

- Bottom Boundary Layer Separation: The presence of mid-water column nepheloid layers over the shelf and slope (Drake and Cacchione, 1987) is direct evidence of transport from the bottom boundary layer into the interior. These layers contain large concentrations of biologically regulating trace metals, such as iron, manganese and cobalt (Martin and Gordon, 1988) as well as fine organic particulates rich in carbon and biogenic silica (Small *et al.*, 1989). Some intermediate nepheloid materials might find their way back into upwelling source waters. Quantitative estimates of the cross-shelf flux of biologically and chemically important components in these layers, and the mechanisms that govern them, need to be determined. Other fundamental issues such as the scales of the detached nepheloid layers which result from BBL detachment are also poorly established due to limited sampling. Early modelling efforts within CoOP are needed to better define the currently unknown physical mechanism(s) leading to BBL detachment and the subsequent formation of intermediate nepheloid layers.

- Eddies: Localized vertical water movement due to eddy processes is potentially an important mechanism for moving biological populations and important chemical species into the euphotic zone and into contact with the atmosphere. A number of modeling studies have indicated specific scenarios that can lead to strong vertical velocities (Onken, 1990; Woods, 1988), but the connection to actual (i.e., observed) flow structures such as coastal jets has generally not yet been made. An exception is the work of Pollard and Regier (1992) from FASINEX (Frontal Air Sea Interaction Experiment) in which maps of vertical velocity were diagnosed from the potential vorticity field in the vicinity of a strong meandering frontal jet in the North Atlantic. Another observational example of localized

upwelling is the occurrence of frontal shear instabilities on a filament in the California Current system reported by Washburn and Armi (1988). A limitation of these studies is the lack of ancillary biological and chemical observations. The strong vertical velocities (order 10's m/d) and areal extent (10's km^2) of the eddy features make them potentially important vertical transport mechanisms over an upwelling-dominated continental shelf, where eddies appear to occur in association with the upwelling front (O'Brien *et al.*, 1974). These eddies may play a dual role of advecting nutrients and seed populations upwards and in subducting water masses they may remove populations and particulate organic carbon downwards. This is an area in which early modeling efforts on finite amplitude frontal instabilities can help define an observational program. Moreover, there is evidence off central California that eddies of a more oceanic nature centered over the continental slope can affect lateral distributions of temperature over the shelf (Kosro, 1987; Huyer *et al.*, 1991) and that their presence seems to enhance the export of particulates to deeper water (Washburn *et al.*, 1993). The topic of how eddies penetrate the shelf has received relatively little dynamics study to date.

- Turbulent Entrainment: When the turbulence level within a boundary layer increases due, for example, to increased wind or bottom stress, the turbulent region expands into the vertically adjacent, much less turbulent waters. The net effect is to transport some of the properties of the interior region into the well-mixed boundary region. Thus, entrainment can bring biologically regulating materials (nutrients and micronutrients) into the euphotic zone, even in the absence of vertical advection. The biological and chemical importance of this process is well-appreciated in the open ocean, where it can be a major limitation on production. While it is known to be involved in wind-driven coastal systems, its detailed role is not well quantified near the surface, and is largely unevaluated in the bottom boundary layer.

- Benthic to Euphotic Pathways: Nutrient budgets for continental shelves (e.g., Mantoura *et al.*, 1991) generally demonstrate that a large portion of the nutrients consumed in the euphotic zone must have been recycled in the shelf sediments. The pathways by which these benthic-to-euphotic transports take place are not well known. For example, do the nutrients in the sediments primarily reach the water by the action of benthic organisms (irrigation), by molecular diffusion through a laminar layer, or during sediment suspension? Once the nutrients reach

the water column, by what path do they reach the euphotic zone? One likely idea is that they are transported shoreward in the bottom boundary layer and then upward in the inner shelf region, but alternatives involving the interior water column are not at all unlikely. The different pathways need to be evaluated.

Other pathways for chemicals and particulates between the interior and boundary regions are possible, for example particle sinking and transports associated with vertically migrating organisms. The working group selected the above list as being likely to be important for structuring biological fields over the shelf, and capable of being discussed intelligently by the attendees.

3. Importance

Ultimately, new coastal ocean productivity is governed by the processes that bring biologically regulating chemicals into the euphotic zone. In most cases, the interior is believed to be the channel through which such transports take place. The nutrient-rich, nearly nonturbulent source waters advecting onshore to supply coastal upwelling would be an example. In addition, the interior can serve as a sink to materials originating in the euphotic zone, for example through the frontal subduction of phytoplankton. Subducted phytoplankton can then present a different feeding environment for zooplankton, made less vulnerable by the protection from visually guided predators. The interior is likely the site of nutrient and chemical recycling, particle aggregation and disaggregation, trace metal reactions, and particle scavenging (to name a few processes), adding to its importance the role of a reaction chamber. In sum, interior–boundary layer interactions are expected to be a major source for supplying the biologically regulating chemicals (both "new" and recycled) that fuel highly productive coastal upwelling ecosystems, as well as the less productive systems prevalent during winter conditions.

4. Approach

4.1 General Considerations:

Gaining a quantitative understanding of interior–boundary layer interactions will be a challenging enterprise, involving both models and observations. The modeling

effort will have to address some issues that have never been treated in the past, even on a single-discipline level. The observational campaign will have to resolve features that are transitory both in space and time. Our general lack of information about some effects will require understanding and resolving the important scales of biological, chemical, geological as well as physical and meteorological variables. Because of the need to use models to generate plans and hypotheses, and to use state of the art, rapid-sampling instrumentation, modeling and instrument development efforts should be funded approximately two years before the onset of major field efforts.

It is important to consider what biological variables are of interest. There is an inevitable tradeoff between technological ease of measurement (which usually also means ease of interfacing with physical measurements in scale) and completeness of information. At one extreme are "bulk" properties — e.g., total phytoplankton pigment, displacement volume, or total acoustic backscatter of animal-sized particles, etc. At the other extreme, each organism is categorized to species, age, physiological and/or reproductive state, and genetic sub-population. These admittedly tedious categorizations both aid in interpreting the observed patterns of bulk properties and permit inferences about the food web consequences of these patterns.

A reasonable intermediate is "accessory pigment taxonomy" for phytoplankton (i.e., distinguishing major groups by their non-chlorophyll accessory pigments) and size distribution ("equivalent spherical diameter") for phyto- and zooplankton. Both approaches lend themselves to electronic sensing, although frequent calibration by removing samples from the ocean will be necessary.

The best approach to biological surveys is nesting. For zooplankton (in order of increasing resolution and decreasing scale), this would mean (1) a large quantity of total acoustic backscatter (collected with an ADCP) data from many locations, (2) intermediate spatial/temporal coverage (focussed at times on places of special interest) with multi-frequency or overlapping beam devices which permit greater resolution of individual target strength, and (3) still fewer net or pumping measurements (again focussed on times or places where detailed information would be most revealing) with complete categorization of the dominant types of organisms.

Thoughts about the location of a field study were complicated by the rather different characteristics that exemplify central Oregon versus northern California during the upwelling season. Oregon usually has an upwelling front over the shelf during the

summer, and this structure helps to define biological fields and provides a locus for subduction and unstable currents. The wind sometimes reverses direction to downwelling-favorable during the summer. Off northern and central California, upwelling fronts are not so obvious (if even present) over the shelf, and the winds rarely reverse direction. These rather different characteristics make it attractive to carry out simultaneous efforts in both regions in order to contrast results. Simultaneity is important to remove any question of differences being due to interannual effects such as El Niño. Similarly, it is important that, whatever sites are chosen, a good set of historical observations are available to place results into interannual context.

It is also important that the period of field work be placed in a historical context — how "typical" of a longer-term mean was the situation studied. This criterion may not seriously constrain the region of study in terms of meteorology, but it is a consideration in terms of biological properties — especially species composition — where there is much more published information for some regions (e.g., the Oregon coast) than for others (e.g., the central California coast). In any case, serious consideration should be given to repeating historical sampling patterns (if any) in the chosen region. Even if these patterns are technologically or statistically crude by contemporary standards, reproducing them may help place the results of the CoOP study in a larger context. Because interannual to interdecadal variability is quite large in scale, if multiple sites for CoOP studies are chosen, it may be sufficient to refer only one of them to a long-term base of biological data.

Meteorological considerations will also play a role in selection of study sites. The central Oregon coast provides a more simply-structured environment meteorologically because of a uniform coastline and inshore topography. In contrast, and perhaps of value in a comparative study, the northern California coastline includes capes and headlands that can generate complex atmospheric circulations and, in turn, complex stress patterns. Furthermore, the Klamath Mountains inland can produce complex surface pressure patterns over the ocean when the upper level flow is from the east. Because of the simpler external structure of the Oregon coastline, some aspects of the atmospheric coastal "jet" may be more easily studied. For example, the summertime pattern of atmospheric baroclinicity produced by northerly flow over a narrow cold upwelling zone would be more tractable to study. In terms of ease of atmospheric instrumentation, a narrow shelf area and close-in ocean front and jet would be more easily available to the 10–20 km range of LIDARS and CODARS. With these instru-

ments, the surface currents and overlying wind structure could be mapped easily and more easily related to changes in the underlying current systems.

4.2 Modeling Studies

A series of disciplinary and interdisciplinary modeling efforts will be required. These studies may often not be numerical models (in fact, it may sometimes be desirable to avoid such an approach, especially initially), but could involve traditional analytical or laboratory approaches. The initial goals of this program will be:

- to understand the dynamics of different exchange and transformation processes,
- to make tentative evaluations of their importance for biological, chemical or sediment transport,
- to estimate which chemical and biological processes are likely to be important in shelf waters, knowing the appropriate rates and the approximate residence times expected for interior waters,
- to isolate observable signatures that will help to quantify fluxes of chemicals and particulates and to test hypotheses, and
- to seek preferred locations in the ocean where processes take place.

Some of the processes mentioned above have already been modeled, including with "two-discipline" (e.g., physical–biological) models. Others have not been modeled at all, to the group's knowledge, and require both disciplinary and interdisciplinary approaches. Three problems deemed to be particularly important to address before field studies are:

- frontal subduction,
- bottom boundary layer separation,
- upwelling and downwelling in eddies and coastal jets.

These studies should be undertaken and at least partially completed before detailed field work is planned in order to make well-informed planning decisions.

Models will be important throughout the process study. In the planning stage, process-oriented models can help to sharpen the questions and suggest sampling schemes.

During field work, data-assimilative models may prove useful for planning detailed field work and to synthesize observations. During the analysis stage, models can be used to explain observed phenomena and to express the required quantitative synthesis. Strong model-observation coupling will greatly enhance the CoOP effort, while loosely coupled efforts will result in an incomplete synthesis.

4.3 Observations

The program will require an integrated set of observations from ships and moorings. We believe that the shipboard observations will, at a minimum, require 2 ships operating in the 'rabbit' and 'tortoise' modes: One ship (rabbit) towing an undulating body (SeaSoar or similar) would define spatial variability of the physical, chemical and biological property fields. Surface mapping of nutrients and other chemical properties will also be undertaken from this ship. The second ship (tortoise) will simultaneously conduct a series of physical, chemical and biological studies at a set of stations across the margin. Station locations can be defined using information obtained in near real time from the rabbit ship. These studies will be designed to define the rates and mechanisms of a set of processes that control the interaction of the variable fields. An array of moorings on the margin would be necessary to determine the temporal variability in physical, chemical and biological properties within the study area, as well as to close budgets.

Much of the observational program will be possible due to recent progress in sensor design. Advances in bio-optical instrumentation (e.g., the Western Environmental Technical Labs AC-9) have made it possible to map the scattering and absorption of oceanic particulates in several wavebands. These measurements translate into information about particle type (e.g., phytoplankton, detritus, sediments, etc.) and abundances and will allow high-resolution sampling. Other new sensors, such as the "pump and probe" can yield highly detailed information about the physiological state of phytoplankton (Falkowski *et al.*, 1992). Continuous chemical sensors for nutrients such as nitrate (Johnson *et al.*, 1990) and trace metals (Coale *et al.*, 1991) can be used to relate this information to the dissolved chemical field. These sensors can operate on undulating vehicles and provide chemical maps with a resolution that begins to be comparable to that of the physical parameters. The detection limits for dissolved metals that can be obtained in situ must be extended to lower concentrations for work in the surface layer by adapting more sensitive chemistries. There are clear pathways to this goal, which are described in the literature (Hirayama and Unohara, 1988), and

considerable progress has been made already. Underway measurements of turbulence microstructure, currents and water mass structure allow these biological and chemical observations to be placed in a context where their interactions with transport processes can be examined in detail.

Many of these instruments are now deployable from moorings, or will be in the near future. These developments make possible the determination of many biological (Dickey *et al.*, 1991) and chemical processes (Wallace and Wirick, 1992), in addition to physical oceanographic measurements. It thus becomes possible to estimate rigorous budgets of chemical and biological variables over the shelf and slope using a three-dimensional moored array.

4.3.1 The Rabbit

The Rabbit ship would conduct a series of cross-shelf and along-shelf surveys in the study areas, while operating an ADCP and towing an undulating body equipped with a suite of physical, biological and chemical sensors. Surface mapping of nutrients, dissolved gases, trace metal distributions (and other chemical constituents) and plankton would also be done. Determination of metal concentrations will likely require that a non-contaminating pumping system be towed from the side of the ship, as most flow-through seawater systems are not clean enough for trace metal work. A suite of metals such as cobalt (Sakamoto-Arnold and Johnson, 1987), copper (Coale *et al.*, 1991) and manganese (Chapin *et al.*, 1991) can be determined in surface layers at time intervals on the order of 5 minutes per sample. Periodic surface samples for biological properties will also need to be collected to calibrate sensors in the undulating fish. The net result of this sampling scheme should be spatially well-resolved measurements representing the chemical, phytoplankton and zooplankton, as well as the physical, fields.

4.3.2 The Tortoise

A complete understanding of the processes regulating biological and chemical transport through the interior will require a series of detailed studies using techniques, such as net or pump sampling, that are not amenable to high resolution mapping studies. For example, the determination of the rates of flow of chemicals into the benthic boundary layer from the sediments might require the deployment of free-vehicle benthic flux chambers to determine chemical fluxes into the boundary layers. Tripods equipped to determine horizontal and vertical current shear into the interior will be needed to estimate rates of chemical transport. Hydrocasts into the BBL will be required to as-

sess the vertical distribution of chemicals, which will serve as a check on predictions of coupled geological–physical models of upward transport. Finally, assessment of the distribution of short-lived radio-isotopes with strong sources in the BBL, such as 222Rn, may be useful tools to quantify mechanisms by which material is transported into the interior.

Programs that will likely need to be conducted are:

- studies of particulate and chemical transport by plumes,
- role of the sediment community in remobilizing biologically regulating chemicals,
- mechanisms by which dissolved chemicals in the BBL are transported to the surface layer,
- rates of scavenging of biologically regulating metals in the interior and surface layers,
- species counts and rate measurements for plankton.

4.3.3 Moorings

Temporal variability of physical–biological–chemical interactions in the water column are best assessed by deployment of moorings with a suite of physical, biological and chemical sensors for long periods. Chemical sensors for nitrate that will operate for 2 to 6 month periods on moorings are now undergoing preliminary testing and will likely be ready for this program. Studies of meteorological interactions will also require that the moorings have appropriate atmospheric sensors. Measurements of turbulent transport from the BBL into the interior also require that the moorings have an appropriate suite of sensors located within the BBL such as BASS (Benthic Acoustic Stress Sensor). Acoustic sensors such as moored ADCPs (Acoustic Doppler current profilers) will be particularly important because of their ability to measure currents well and at the same time produce information on zooplankton abundance. A moored array should have about the same spatial coverage as the central three mooring lines of the CODE array (Winant *et al.*, 1987).

4.3.4 Atmospheric Coupling

Because much of the interior circulation and cross-shelf transport is ultimately driven by surface wind stress and its variations, a coordinated atmospheric measurement and modeling program is critical to understanding cross-shelf transports. With

limited moorings to provide direct measurements of the surface stress field, atmospheric models using data assimilation will be important for characterizing spatial and temporal variability of the surface stress field. Intensive campaigns using shore-based instruments such as CODAR (Coastal Ocean Dynamics Applications Radar) and Doppler LIDAR can provide detailed case studies to validate coupled ocean–atmosphere models. Doppler LIDARS operating in a dual mode can map the wind field within a few meters of the surface at a 300 m horizontal resolution. CODAR measurements could provide surface currents over a region of about 20 km on a side. Buoy-mounted flux measurements could characterize the fluxes of momentum and gases as a function of stability, wind and other governing variables. Aircraft measurements can give snapshots of atmospheric conditions as well as of surface ocean variables (color, surface temperature).

5. Summary

The interior of the water column is expected to be the largest section of the shelf water column. We anticipate that it is the locus of a number of important chemical and biological transformations, and by its nature, it is expected to exchange waters with all the other shelf subregions. Given its nature as the central junction for exchange, our ideas about how to address interior problems inevitably overlap with the results from other working groups. We chose to retain any redundancy in the belief that it is better to include too much rather than too little. At the same time, our working group certainly did not include a complete cross-section of ocean disciplines, so we readily acknowledge that there are likely holes and weak points in our findings.

Appendix 5: Frontal Processes

Rapporteurs: Ian Perry and Jane Huyer
Participants: Mark Abbott, Jack Barth, Curt Collins, Tim Cowles, Mary-Lynn Dickson, Percy Donaghay, Peter Franks, Dale Haidvogel, Jane Huyer, Burt Jones, Mike Kosro, Julie McClean, Jim Overland, Ian Perry, Bob Smith, Leonard Walstad, and Richard Wiener.

The Working Group defined "Frontal Processes" in the context of this CoOP workshop to be the alongshore and cross-shelf currents and mixing related to the formation, maintenance, and perturbation of fronts associated with the wind-driven upwelling system on the west coast of the United States. Coastal upwelling fronts define sharp, continuous and persistent boundaries between oligotrophic and productive waters on the continental shelf. Model studies and observations suggest that these fronts can act both to enhance and to inhibit the cross-shelf transport of momentum, chemical and biological constituents, heat and salt. Materials can cross the front, be carried along the front, or remain inshore of the front by a variety of processes; their relative importance will determine the nature of the net offshore transport and affect the ecosystems both inshore and offshore of the front. Recognition that these are strongly time and space-dependent processes led to the following central question for the Frontal Processes Working Group:

> How does the coastal upwelling front, over the continental shelf and slope in a wind-driven upwelling system, act to regulate the activity, distributions, and cross-shelf exchange of plankton, sediment and chemical constituents?

Importance

Meteorological: The time scales for coastal upwelling and downwelling events are associated with shifts in the large-scale atmospheric weather regime. This transition occurs at intervals of 3–7 days in winter and generally longer intervals during late spring and summer. Transitions are often marked by abrupt wind reversals associated with propagating coastal-trapped atmospheric waves or density currents (Dorman, 1985). The wind field over the coastal zone out to 100 km can be uniform if the atmospheric stratification is weak and the onshore component of the wind velocity at 850 mbar is strong (Winant *et al.*, 1988). However, more

typical is the formation of an alongshore coastal atmospheric jet with wind speeds greater than in the weather system offshore or at the coast (Elliott and O'Brien, 1977; Beardsley *et al.*, 1987). This variation in the wind field across the shelf is important to the spatial variability of surface layer Ekman divergence. However, the quantitative relationships among the intensity, timing, and offshore distribution of the alongshore jet, the atmospheric sea level pressure pattern, stability and the slope of the coastal orography are unknown. The oceanographic front represents a major change in the surface boundary conditions and may set up a baroclinic zone in the lower atmosphere and amplify the cross-shelf gradient in surface stress. This increase in wind, and wind shear perpendicular to the front, may contribute to instabilities along the front. However, detailed observations are generally lacking. Improved understanding will increase the accuracy of coastal weather forecasts, which at present are often not well resolved by large-scale weather prediction models.

Physical: While the formation of the coastal upwelling front is relatively well understood (Allen, 1973; Mooers *et al.*, 1976), the processes leading to its evolution, persistence, offshore migration, and ultimate decay are still not well known. For example, what role do eddy motions play in the maintenance and spindown of coastal upwelling fronts? What are the dynamical mechanisms that act to drive the front across the topography? Interactions of the frontal circulation with wind variability and alongshore topographic variation is a major source of three-dimensional mesoscale variability on the shelf, the understanding of which is a major goal of physical oceanography.

Biological: Upwelling fronts are locations of enhanced biological activity and significant property gradients (Small and Menzies, 1981; Kokkinakis and Wheeler, 1987; Hood *et al.*, 1992). However, the processes which produce such gradients and activity, and in particular their coupling with the physical dynamics, are not well understood. To what extent are the strong gradients produced in situ, or due to convergent physical circulation? To what extent are temporal and spatial variations in new and regenerated phytoplankton production forced by a wind-driven front, and what are the influences of these physical processes on phytoplankton community structure and trophic interactions? How do seed populations and initial conditions affect the dynamics of phytoplankton and zooplankton blooms at such fronts, and what is the fate of this organic carbon (export off the shelf,

recycling in the pelagic zone, or transport to the benthos)? How does the front affect the cross-shelf transport of larvae and recruitment to adult populations? Upwelling fronts are therefore important to the total productive capacity and characteristics of U.S. west coast continental margins.

Chemical: Very little is known of the cross-shelf distributions and dynamics of most of the trace elements and rare chemicals on the west coast continental margin. Many of these chemicals can be used as tracers of water mass origins and "time clocks." For example, radon can be used to determine the time a particular water mass has been in contact with the atmosphere (Kadko *et al.*, 1991). Understanding the interactions of physical and chemical processes about upwelling fronts will help to interpret distributions and changes in the chemistry of continental shelf waters.

Geological: Convergent circulation at upwelling fronts can accumulate sedimentary materials, which may be deposited to the bottom as the dynamics or location of the fronts change. Long-term locations of such frontal systems may be identified by the distribution of fine sedimentary material on the bottom. Studies of the physical dynamics of frontal regions are important for understanding the distribution of sedimentary materials on the bottom of the shelf, and the flux of materials off of the continental shelf.

Critical Interdisciplinary Issues

The critical interdisciplinary issues relate to understanding how fronts regulate the activity, distribution and transport of properties and materials across the shelf. Two basic frontal regimes appear to be important for cross-shelf exchange during the upwelling season: (i) the regime in which the upwelling front lies approximately parallel to the shelf isobaths, and (ii) the regime in which the upwelling front crosses steep topography. Although the former regime is two-dimensional to first order (in that alongshore gradients are weak compared to on/offshore gradients), the higher-order three-dimensional and time-dependent effects are likely to be of great importance to cross-shelf exchange, as local or episodic convergences lead to mixing, sinking or subduction of water properties and plankton populations. The latter regime is inherently three-dimensional, with alongshore gradients of velocity, water properties and popu-

lations approaching the magnitude of the on/offshore gradients, while the along-front water-depth changes by more than a factor of twenty as the front crosses the slope.

i. *Cross-frontal circulation and mixing over the shelf.*

These generally represent small-scale processes, and belong to the generic class of questions dealing with exchange processes across fronts of many different origins. In the context of this project, the relevant questions are (a) to what extent do such exchanges occur due to the mean circulation, and whether these are driven by the average alongshore wind stress or by the small-scale wind stress curl generated by the orography; and (b) to what extent are exchanges driven by the fluctuating circulation? Fluctuating (turbulent) circulation may be driven by differential small-scale mixing, for example forced by tides, internal waves, shear, and bottom boundary layer effects. These fluctuating circulations can also have dramatic impacts on biological, chemical and geological properties and processes about the frontal region. In addition to directly affecting property distributions, turbulent mixing can be an important mechanism for exchange of nutrients across the front, both vertically and horizontally, which is critical for enhanced phytoplankton production. Moderate rates of turbulence have also been theorized as an important mechanism enhancing contact rates between predators and prey in zooplankton feeding dynamics. Larger-scale processes such as eddy formation and meandering (inherent instabilities) and direct wind-forced fluctuations are also relevant to this problem of cross-shelf exchange of properties and materials. Important issues are the time and space scales of these features, their duration, frequency of formation, and preferred locations. (c) A third class of processes related to fronts and cross-shelf exchange are the broad-scale circulations such as convergence (subduction) zones. What are their physical dynamics, and their relevant scales? It is unknown to what extent high biological activity within frontal regions is driven by convergent flow or in situ production. These processes also potentially affect bottom sediment patterns and phytoplankton distributions and dynamics (e.g., through passive settling), and the distributions and responses of vertically-migrating zooplankton, for which purely passive modeling of the circulation is inadequate.

ii. *Processes that occur as fronts cross the continental slope.*

This class of cross-shelf transport problems affected by upwelling frontal systems has the potential to carry large amounts of materials, heat, momentum, etc.

into the deep ocean, for example from upstream (on-shelf) sources to far offshore through the frontal jet. There are two (related) issues on the west coast of the U.S: what causes the front to leave the shelf, and what happens to it (dynamically) as it leaves the shelf? Does it leave the shelf due to local wind stress variations (e.g., the curl resulting from headland effects), due to alongshore topography, or due to finite amplitude meanders? Potential biological consequences include the impacts to phytoplankton biomass and species composition of subduction to greater depths due to vorticity changes as the front moves into deep water, changes in nutrient inputs, and changes in the zooplankton grazer community (e.g., exposure to vertically-migrating deep-water zooplankton). The importance to biological processes of "founder" effects, i.e., differences in species composition in the areas where the front and jet first form and begin to move offshore, are also not well investigated or understood. The possibility of a succession of fronts formed across the shelf and moving offshore at different rates (likened to peeling off the layers of an onion), and regions of temporal and spatial discontinuity in the frontal systems were also noted as potentially important features applicable to all disciplines but not well studied or understood.

Approach

The important question of how frontal processes effect cross-shelf exchange is inherently three-dimensional, time-dependent, interdisciplinary, and complex. It requires an integrated multidisciplinary approach that includes both modeling and in situ measurements.

Present models are not fully adequate; further development should start soon so that process modeling can be completed in time to guide the measurement program. Development of three-dimensional biological and chemical models with forcing provided by three-dimensional physical models is particularly needed. Ocean models should be forced with the time and space scales appropriate for idealized coastal atmospheric circulation. A study of the effect of the coastal wind jet could be accomplished with existing oceanographic models. The role of headlands would require a simulation of the atmospheric conditions, but a process study using estimated alongshore variations in wind stress may be profitable and could be accomplished using current ocean models. To study the interaction of the coastal atmosphere and ocean will require

development of a fine-resolution coupled atmosphere–ocean model. An understanding of the resolution requirements and development of sub-grid scale parameterization are of importance to any modeling of the coastal margin. Also, regional models with open boundaries over steep topography will be required for process studies where a periodic channel is inappropriate.

In situ measurements must include observations of a wide variety of variables (meteorological, physical, chemical, biological and geological), using complementary sampling techniques (synoptic surveys, fixed time-series, drifting buoys, etc); these must be made over at least six months in each of two upwelling seasons to ensure several realizations of the dominant temporal cycles. Detailed cross-frontal measurements should be made both in the upstream regime where the front lies over the shelf, more or less parallel to the isobaths and coastline, and in the region where the front crosses the shelf-break and continental slope; measurements should also be made across the shelf south of the separation point (typically near a cape or headland).

Experimental Design

The following "strawman" experimental design is presented only to exemplify the kind of strategy needed to address these questions. It is not the intent to specify exactly either the modeling effort or the measurement program, and we recognize that alternate designs may also be successful. Nevertheless, we believe it is valuable to present this design to convey the magnitude and scope of a suitable program.

Domain

- The study domain should extend about 100 km offshore, from the inner shelf (e.g., 30 m isobath) extending offshore past the foot of the continental slope by at least 50 km (twice the internal Rossby radius).
- It should extend about 200 km alongshore, and include both sampling upstream, downstream, and offshore of the point where the front crosses the slope, and sampling of the upstream regime where the front lies over the shelf.

Integrated Sampling Strategy

To understand the three-dimensional and time-dependent frontal processes effecting cross-shelf exchange, complementary sampling strategies are needed:

- Remote sensing to monitor the position of the front. Measurements might include satellite AVHRR and color, shore-based ocean surface radar systems (e.g., CODAR or OSCR) to measure surface currents, and acoustic tomography.

- Moored arrays to provide time series at locations through the front both across the shelf (e.g., along lines a and b, Figure 3) and along the slope (line c, Figure 3), and across the shelf downstream of the separation point (line d, Figure 3). These would include: meteorological buoys to measure offshore and alongshore gradients in the wind stress and air temperature; moored current meters (especially bottom-mounted ADCPs); moored optical and chemical sensors; and moored dissipation sensors.

- Synoptic surveys to make detailed surface and subsurface measurements through the front. Surveys should include rapid repetitions of a cross-frontal section over the shelf (near line a or b, Figure 3) and another cross-frontal section along the slope (line c, Figure 3), and a series of cross-frontal sections separated by a few kilometers downstream (e.g., from line a to b, and from b to c Figure 3). Each cross-frontal section should be completed within several hours to ensure synopticity. There should also be a few cross-shelf sections downstream of the separation point (near line c, Figure 3). Surveys would include rapid measurements of surface winds, subsurface currents (ADCP), near-surface water properties (T, S, fluorescence, particle size spectra, macro-nutrients, Mn, etc.), and subsurface properties (T, S, optics, fluorescence, particle size spectra, e.g., using SeaSoar); rapid measurements of turbulence and dissipation should also be made.

- Drifting buoys to provide quasi-Lagrangian measurements of velocity, temperature, optics and chemistry. These should be equipped with GPS receivers to provide accurate velocity estimates over short time-scales. A few might also be equipped with a surface-mounted ADCP, if possible.

- Neutrally-buoyant floats to provide Lagrangian estimates of vertical and lateral velocity. Such floats should be deployed on several different isopycnals, across the front well upstream of the separation point (e.g., near line a, Figure 3), and along the shelf inshore of the front. Such floats provide an exciting new tool to determine the importance of isopycnal subduction and vortex stretching, particularly in the location where the front crosses steep topography.

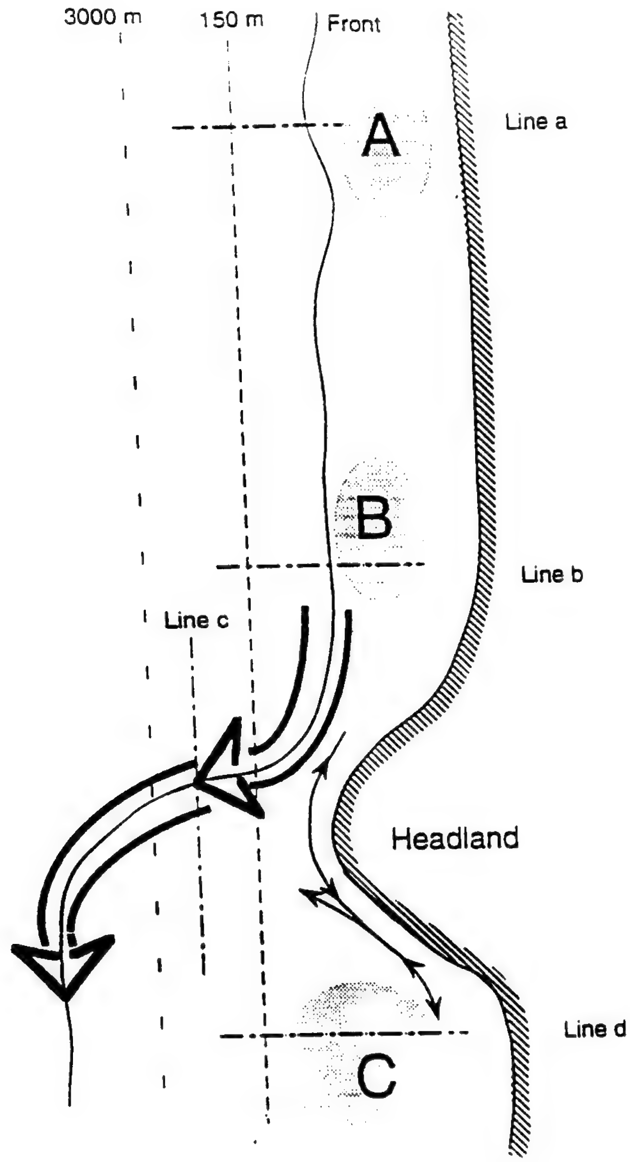


Figure 3: Schematic of the domain for an experiment to study cross-margin exchange by upwelling fronts. Observations should be made in a region where the front crosses the continental slope, and in the upstream region where the front lies over the shelf, more or less parallel to the coast and isobaths. Large arrows represent the intense currents along the front. Thin arrows represent the inner shelf currents whose direction fluctuates with the wind. Lines a, b, c and d represent sections to be repeatedly sampled. Moorings would be deployed along these lines; additional buoys would be required to resolve the local wind stress curl. Areas A, B and C represent potentially different plankton ("source") populations.

- Biological process studies. Most biological processes (growth rates, feeding, species interactions, source effects) and micro-nutrient distributions cannot yet be measured synoptically but are nevertheless important for understanding cross-margin exchange and its effect on the ecosystem. A few cruises to study these processes are needed.

Modeling

Theoretical and numerical modeling is required for detailed experimental design, especially for studying biological–physical interaction processes but also to guide the placement of moorings, and the design of survey tracks. Modeling is also required as part of the analysis of the field measurements — measurements can never answer all of the important dynamical questions, and models will play an important role in interpreting the results of the measurement program. Specific modeling issues to be addressed include:

- Coupled biological-chemical-physical models need further development to explore complex processes such as the biological response to rapid changes in vertical advection or surface wind stress (affecting vertical mixing, light level, depth and nutrient concentration), and the biological effects of strong shear or turbulence.

- Present circulation models cannot resolve the small-scale dynamical processes likely to occur within the upwelling front. Resolution requirements and sub-grid scale parameterization must be understood.

- Coupled ocean–atmosphere models, with resolution appropriate for resolving the coastal jet and the horizontal and vertical structures within the marine boundary layer, are needed to study the interaction of the front and the atmosphere. These models are also needed to aid in designing the atmospheric observational system.

- The impact of temporally and horizontally variable wind stress upon oceanic fronts has not been studied. Current ocean models can be forced with realistic small-scale wind stress but have not been. An understanding of the effect of the coastal wind jet and the potential importance of the marine boundary layer is needed.

- Three-dimensional circulation models with stratification, steep topography, and open boundaries need further testing and development.

Appendix 6: Abstracts of Talks

Coastal Meteorology – Richard Rotunno

Introduction

Coastal meteorology is the study of meteorological phenomena in the coastal zone caused, or significantly affected, by the sharp changes that occur between land and sea in surface transfer and/or elevation. The coastal zone is subjectively defined as extending approximately 100 km to either side of the coastline. Examples of coastal meteorological phenomena include the sea breeze, sea-breeze-related thunderstorms, coastal fronts, marine stratus, fog and haze, enhanced winter snow storms and strong winds associated with coastal orography. Increased knowledge of several or all of these is important for studies in the physical and chemical oceanography of the coastal ocean. The practical application of this knowledge is vital for more accurate prediction of the coastal weather and sea state which affect defense, transportation and commerce, and pollutant dispersal.

The dynamical meteorology of the coastal zone may be thought of in terms of three subsidiary ideal problems. The first problem is one where the coastal atmospheric circulation is primarily driven by the contrast in heating, and modulated by the contrast in surface friction, between land and sea. The second problem is one where the primary influence is due to the steep coastal mountains whose presence may induce strong alongshore winds, and other complex flow patterns. The third class of phenomena broadly consists of larger-scale meteorological systems that, by virtue of their passage across the coastline, produce distinct smaller-scale systems. For wind-driven systems of the U.S. west coast, we focus here on the second problem.

The Atmospheric Boundary Layer

The transfer of heat, momentum, and water vapor between the atmosphere and the lower surface (be it land or sea) is basic to these three ideal problems. We consider first the approximately 1 km-deep layer of air adjacent to the surface called the atmospheric boundary layer (ABL). Study of the ABL is intended to reveal how the effects of surface transfers are distributed upward. The best understood model of the ABL is when it is

cloud-free and convective and horizontally homogeneous. However, near the coast, the ABL is anything but. Stratus, fog and drizzle complicate the situation as they depend on a complex interplay between cloud physics, radiation and turbulence. Perhaps the most severe scientific problem is how to treat boundary layers that are not horizontally homogeneous. Over land, there is still significant uncertainty on the nature of surface transfer from terrain with variation in vegetation and usage such as occurs along the coast. Over the ocean, those surface transfers are determined by the sea state, which in turn, is determined by the atmospheric flow, which is influenced by the surface transfers, etc. This fundamental coupling has been long recognized, however there is another order of complexity over the coastal ocean because there the sea state is significantly influenced by the ocean shelf.

The Influence of Orography

Coastal mountain ranges can significantly affect coastal meteorology. In many situations the coastal mountains act as a barrier to the stably stratified marine air; thus air with a component of motion toward the barrier at great distance must eventually turn and flow along the barrier. Also the coastal mountains may act like the side of a basin within which the marine air is contained; under the influence of the earth's rotation, waves known as 'Kelvin waves,' may propagate along the basin-wall-like coastal mountain. Special boundary-layer flows are also observed under the influence of the coastal mountains. For example, during the Coastal Ocean Dynamics Experiment (CODE), a strong alongshore jet was documented. It had a strong diurnal component as evidenced by the depression on the marine inversion near the coastal mountains during the day. The boundary layer structure showed interesting complexity inasmuch as the potential temperature was well-mixed to the inversion but the wind speed increased strongly through the same layer. Phenomenon that appear similar to flow separation in classical fluid dynamics also occur in the lee of capes and other coastline salients. These types of motion are important components of the meteorological problem in these coastal regions.

Interactions with Larger-Scale Systems

Examples of these effects include cyclogenesis enhanced at the east coast of the U.S. as upper-level disturbances cross the Appalachians and encounter the strong baroclinic zone at the coast, and flow along the coast in winter with strong cooling of the air on the landward side leading to the formation of fronts.

Influences on the Coastal Ocean

In general, the ocean affects, and is affected by, the atmosphere. In the northern hemisphere, an along-coast wind with the coast on the left brings the sea into motion in the along-coast direction, due to the Coriolis effect the water motion is deflected away from the coast necessitating its replacement by water from below — this phenomenon is know as coastal upwelling. The water from below is colder, and in general is of different chemical and biological composition. The details of the cross-shelf transport (necessary to feed the upwelling) are poorly understood, since the ocean is responding to atmospheric influences over a large range of time and space scales. This wind-stress data from CODE shows a considerable standard deviation to the mean. Also the alongshore ocean currents may be highly irregular. There is evidence that some of the irregularity is due to wind-stress variations along and across the coastal zone.

Also the colder water along the coast now means there is yet another across-coast temperature difference that can produce changes in the atmospheric circulation, which can affect the ocean, etc. Interactions of this nature are important to the understanding of the coastal ocean, and the chemical and biological processes occurring there.

Capabilities and Opportunities

Observations

The present observational network of routine in situ data is not adequate for most applications. The coastal rawinsondes, especially over the west coast, are very sparse. The buoy network is sparse and only measures conditions near the surface. There are transient ship reports that supplement the buoy reports.

As part of NOAA's observational equipment modernization will offer some improvements and some degradation. NEXRAD will provide an increase in over-water coverage: Doppler winds out to 150 km, reflectivity out to 400 km. Returns from the moving sea surface may possibly be interpreted to get surface winds. No new rawinsondes are planned, and some coastal sondes may be moved inland. Efforts continue to use passive and active satellite techniques to infer the atmospheric and sea state. Surface based remote sensors can give highly detailed spatial and temporal detail in the boundary layer.

Models

The emergence of high performance workstations having substantial fractions of the calculation speed performance and superior throughput of present day mainframe supercomputers will allow researchers to run regional models with high resolution and to conduct numerous sensitivity studies.

Physical Oceanography – Steven Lentz

What are the important physical oceanography problems associated with wind-driven cross-shelf transport processes on the U.S. west coast shelf? I chose to focus on five specific topics. The first three topics are components of the classical two-dimensional wind-driven cross-shelf circulation which remain poorly understood. The last two topics focus on complexities associated with fronts and the fundamentally three-dimensional character of the flow field.

1. Interior cross-shelf circulation:
   The interior cross-shelf circulation is known to have short horizontal correlation scales (e.g., Kundu and Allen, 1976) making it difficult to interpret. Why the interior cross-shelf circulation has short scales is an important unresolved question (Brink *et al.*, 1994). Given the large number of existing observations it seems unlikely that more observations will shed light on this problem in the absence of a more focused hypothesis. Thus, a more concerted modeling effort guided by existing observations seems like the best approach for addressing this question.

2. Bottom boundary layer:
   In contrast to the interior, there have been very few observations resolving the velocity and density structure within the bottom boundary layer. Consequently, there have been few attempts to evaluate even the fundamental aspects of the bottom boundary layer dynamics, such as whether the cross-shelf transport in the bottom boundary layer equals the Ekman transport. The horizontal correlations scales of bottom stress and currents within the bottom boundary layer are also not known. Furthermore, recent studies have pointed out the importance of cross-isobath buoyancy flux to the bottom boundary layer dynamics (Weatherly and Martin, 1978; Trowbridge and Lentz, 1991; MacCready and Rhines, 1991). Consequently, both observations and modeling are needed to begin evaluating and refining our understanding of the bottom boundary layer.

3. Inner-shelf:
   There have also been few observations made over the inner shelf; the region where the surface and bottom boundary layers begin to interact resulting in a divergence in the Ekman transport. This region is also typically ignored in modeling studies, which often place a vertical wall offshore of the inner-shelf.

Consequently, little is known about how the wind-driven shelf circulation adjusts to the coastal boundary condition. Key questions include: How wide is the inner-shelf under various conditions? Is the inner-shelf circulation two dimensional? What are the dynamics? Clearly observations are needed to provide a basis for developing and evaluating models of the inner-shelf circulation.

4. Fronts:
   While there are lots of observations of fronts in coastal regions, for example from satellite images, we know relatively little about fronts. Two examples of fronts over wind-driven shelf/slope regions are the upwelling front which separates cold nutrient rich water from warmer nutrient poor water and the inner-shelf front often seen in models which separates a well-mixed inner shelf region from the stratified midshelf. In the context of wind-driven cross-shelf exchange a key question is to what extent fronts inhibit cross-shelf exchange by, for example, blocking or diverting the cross-shelf circulation, versus enhancing cross-shelf exchange through frontal instabilities. Modeling in conjunction with creative use of existing observational techniques and/or new observational tools are needed to address the difficult problem of studying fronts.

5. Flow adjustment to spatial variations in the wind and topography:
   While there are numerous examples in the literature of short scale variations in the wind or topography resulting in shelf flow adjustment, notably as convergences or divergences, the details of these processes are generally not understood. For example, it has been well documented that there is substantial short scale variability in the wind in the vicinity of capes along the west coast of the U.S. (Winant *et al.*, 1988). However, it is not known how the shelf circulation adjusts to these features in the wind field. Nor is it clear how important such adjustments are to cross-shelf exchange. Modeling studies might provide considerable insight into these processes. Particularly if existing observations such as the CODE data are used as a basis for evaluation and refinement of the models.

Biological Oceanography – Larry Small

Composite seasonal pictures from satellite data between 35–48°N along the U.S. west coast show very high concentrations of surface pigments in a relatively narrow band hugging the coastline in spring and summer, and more diffuse surface concentrations extending further offshore in fall and winter (Thomas *et al.*, 1994). The offshore boundary of the high surface concentrations appears to be the core of a southward-flowing coastal jet which is most intense in spring/summer (when the prevailing winds are from the upwelling-favorable north–northwest direction), and is more poorly defined in fall/winter (when the winds are upwelling-unfavorable from the south–southwest). Filaments of pigment-rich water can extend offshore as the jet itself meanders offshore (usually in areas of prominent seaward topographic extensions such as capes and headlands). In the context of a relatively short (2 year) CoOP field program, one must be aware of interannual variation in the intensity of surface pigment development and in the timing and placement of offshore-extending filaments, in addition to changing seasonal patterns. Diel cycles in biological properties will also occur (in primary production, for example). Finally, because upwelling-favorable winds sometimes give way to periods of calm or even wind reversals during spring–summer, on the scales of about 1–15 days, one must be aware of these "event-scale" phenomena on the relatively rapid redistribution of biological properties from the more typical upwelling distributions.

Typical upwelling distributions at the sea surface in areas of smooth coastal topography show a gradient from relatively cold, nutrient-rich water with little biological biomass at the coast, to a rich, productive band of phytoplankton (mainly diatoms) either within or just to the shoreward side of the coastal jet which sets up anywhere within 10–50 km from the coast (Small and Menzies, 1981; Landry *et al.*, 1989; Hood, 1990). This surface phytoplankton band actually develops as a three-dimensional core, extending to depths of about 25–100 m (the depth depending at least upon wind strength, velocity of the jet, and depth of the water column in relation to the east–west position of the jet). Chlorophyll *a* concentrations can approach about 10 mg m^{-3} in the core, and carbon production per unit of chlorophyll *a* at optimum light can approach a theoretical maximum of 25 mgC (mg Chl$a$)$^{-1}$ hr^{-1}. If the wind shifts from the N–NW to blow from the S–SW, the strong upwelling circulation is damped, and concentrations of phytoplankton are either distributed throughout the near-coast surface waters or (if the upwelling-unfavorable wind event is persistent over several days) they are packed tightly against the coast and may even experience some downwelling at the

coast. Satellite images usually will not show these event-scale phenomena because the images are frequently composites of many satellite passes over a region, and often over several years; however, Landry *et al.* (1989) show the surface band in mid-summer at about 15–25 km, in 34 years of composite data off the Oregon and Washington coasts. Thus, within the time frames of most research cruises and perhaps in longer time frames, event-scale phenomena could affect data interpretations significantly.

With the coastal jet well offshore at a prominent topographical cape (e.g., about 135 km off Cape Mendocino, California, at ~40°N), the chlorophyll *a* gradient is still present from coast to jet under strong upwelling winds, but is "stretched" so that concentrations are not as great either in the chlorophyll core or in the waters shoreward of the core (Hood, 1990). Chlorophyll concentrations of about 2 mg m^{-3} are typical in this core, with maximum productivities up to about 12 mg C (mg Chl*a*)$^{-1}$ hr^{-1}. To the seaward side of the surface jet (whether the jet is positioned close to shore or well offshore), phytoplankton biomass, productivity, and species composition change radically from those on the shoreward side of the jet. Chlorophyll *a* concentrations less than 0.5 mg m^{-3}, maximum productivity at 5 mg C (mg Chl*a*)$^{-1}$ hr^{-1}, and tiny flagellate and diatom cells as opposed to large diatoms, are typical of these waters. The jet front thus appears to set a fairly firm boundary to seaward extension of near-surface properties all along the west coast. Downwelling at the front, and subduction of surface populations to depths below the jet core, may be mechanisms to transport materials seaward of the jet; however, return flows at depth, possibly coupled with the poleward undercurrent, could serve to bring materials back onto the shelf and toward the north again, and thereby help retain populations and seed stocks over the shelf. Off central Oregon at least, with relatively smooth topography and bathymetry, return flow over the shelf originates mainly from about 50–150 m depth at the shelf break (~200 m water-column depth), bringing in relatively "biologically-clean," nutrient-rich water during upwelling winds (Small *et al.*, 1989), and perhaps returning zooplankton populations to the shelf area as well (Peterson *et al.*, 1979). The euphotic zone corresponds roughly to the seaward-moving Ekman layer at the surface, and a bottom nepheloid layer can move slowly either seaward or landward along the shelf bottom, under the mid-depth "clean" layer. This three-layered structure under generally upwelling winds is recognizable through about eight months of the year, breaking down to a more well-mixed condition from about November through February. Extensions of the bottom nepheloid layer off the shelf form immediate nepheloid layers over the continental slope

and beyond, and can often be observed by several measurement schemes hundreds of kilometers off the coast. These intermediate nepheloid layers likely provide an offshore transport "leak" for materials (biogenic silica, various micro-organisms, etc.) that never return to the shelf region (at least within a seasonal time frame). Extremely thin (cm scale) "sheets" of biological matter, as microlayers between the base of the mixed layer and the bottom of the euphotic zone, can persist for significant lengths of time (hours) even in generally energetic environments (T. Cowles, personal communication; P. Donaghay, personal communication), and thus might also provide a mechanism for offshore transport, as well as aggregation sites for zooplankton grazing.

The major problem facing biological oceanographers in strongly wind-driven systems is thus to understand the biologically-generated changes (through growth, death and sinking) imposed upon stocks that are at the same time being rapidly advected and diffused over time in a 3-D fluid field. This is not a new problem. It is one, however, in which we now have a chance to make significant headway because we now have some techniques to allow us to measure certain biological properties in the same time–space scales as the water motions. I feel that in CoOP we must concentrate on loading moored arrays and drifters with in situ fluorometers, transmissometers, absorption meters, and nutrient analyzers to build large, statistically valid, high-frequency data sets. Surrogate measures for hard-to-measure biological properties should be investigated whenever possible, to yield many estimates rather than a few (for example, easily-done bio-optical measurements can lead to models which predict carbon production rates of phytoplankton with good precision). Validation of rapid and/or surrogate measures of course would have to be done at intervals with time-tested techniques, but the development of large data sets in appropriate time–space scales seems the only way to truly marry biological data with physical data to arrive at an integrated model or models of the strongly wind-driven regime off the U.S. west coast.

Finally, there are some important biological and chemical features that do not yet lend themselves to rapid measurement or surrogate estimation; e.g., assessment of certain trace metals and possible trace metal limitation on phytoplankton growth, rates of phytoplankton removal via grazing, shifts in phytoplankton or zooplankton taxa, and radionuclide tracer estimation of scavenging rates. These measurements should be made, albeit with fewer data points at the end of the project period; yet these data should also be better interpreted if analyzed within the context of an integrated biological–chemical–physical model built from compatible data sets.

Chemical Oceanography – Ken Bruland

Chemical oceanographers can play an important role in an interdisciplinary CoOP program focussing on coastal upwelling systems of the U.S. west coast, particularly in obtaining a quantitative understanding of the processes that dominate the production (or sources), transports, transformations and fates of biologically, chemically, and geologically important matter in these regimes. This includes studies of chemical processes which regulate the production and structure of the upper ocean biological community, the transformation and fate of particulate matter, and the utilization of diverse chemical tracers to address the CoOP goals.

Trace metals are of interest with respect to their potential importance in controlling the production of blooms of large diatoms and in influencing phytoplankton species composition in coastal upwelling zones (Sunda, 1988; Morel *et al.*, 1991; Bruland *et al.*, 1991), as well as being useful as tracers to identify sources, and help determine mixing and transport of water masses. Examples of the former include the bioactive trace metals Fe, Zn and Cu — with Fe and Zn being possible biolimiting nutrients, while Cu is potentially toxic. Examples of using trace metals as tracers include the use of dissolved cadmium as an indicator of upwelling (Bruland, 1980; van Geen *et al.*, 1992), elevated concentrations of dissolved manganese and particulate Al/Fe as indicators of shelf waters, and elevated concentrations of dissolved Pb (and its isotopic ratios) and Al as indicators of oceanic surface water (Flegal *et al.*, 1989).

There have been major advances in the last few years with respect to the chemical oceanography community's ability to measure these trace metals in-situ or near real-time. Shipboard systems for surface mapping with 2 to 5 minute response times have been developed for a number of trace metals. For example, the Galapagos study in the fall of 1993 will have Fe surface data mapped with a resolution approaching 100 meters (Coale *et al.*, 1991). In-situ profiling instruments for nutrients and certain trace metals such as Mn have been developed with 10 to 20 second resolution. Finally, moorings with approximately half-hour response times are currently under development. Nitrate and pCO_2 sensors are currently being tested (Jannasch *et al.*, 1994; Friederich, 1994), and systems could be developed for certain metals (Coale *et al.*, 1991).

There are a variety of natural U- and Th-series radioisotopes that are powerful tracers to the particle-export and cross-shelf exchange problems. Pb-210 is arguably the best tracer for the larger scale questions (Carpenter *et al.*, 1981; Bacon *et al.*, 1994),

while Th-234 can provide useful insight to smaller scale questions of particle transport. Th-230 and Pa-231 can also provide useful insight into the intensified boundary scavenging occurring in these highly productive upwelling regimes. Finally, Be-7 and Rn-222 can provide insight into air–sea exchange processes and be excellent tracers of subduction events (Kadko *et al.*, 1991).

Biomarkers and organic source indicators can be useful in discriminating terrigenous organic materials from marine-derived forms. For example, the phenolic polymer, lignin, and the polyesters, cutin and suberin, are found only in vascular land plants. Coastal plankton versus oceanic counterparts are more difficult to discriminate — possibilities include pigment or lipid differences (Wakeham and Lee, 1992). Different types of phytoplankton can produce characteristic pigments that can be used to trace the transformations and fates of the primary production.

Chemical oceanographers, carrying out studies on trace metals, natural radioisotopes, and specific organic compounds, can provide important data sets with which to address the general CoOP goals and help serve as the linkages between physics and biology and/or geology to make the program truly interdisciplinary.

Geological Oceanography – Richard Sternberg and Christopher Sherwood

In 1977, the Shelf Sediment Dynamics Project (SSDP) was proposed as the first large-scale sediment transport experiment on the west coast. Although never funded, the conceptual model developed for the study (Figure 4) still remains valid and provides a benchmark against which to measure our progress since then. Significant progress has been made on many of the individual components of the model, outlined below:

Sedimentation Model Components

1. Physical forcing: winds, currents, waves.
2. Bottom-boundary layer modeling
3. Sediment transport
   (a) Bedload
   (b) Suspended load
4. Animal–sediment interaction
5. Hydraulic properties of bottom sediments item Stratigraphic model
   (a) Quantify depositional facies
   (b) Interpret sedimentary record
   (c) Interpret geological history

There have been numerous field studies (CODE, SEEP I&II, ISHTAR, STRESS, AMASSEDS, and LATEX) that have addressed many of these topics. Individually funded studies also have been very important in advancing instrumentation and furthering knowledge of specific systems. For example, Healy Ridge and Carson (1987) took advantage of the 1981 eruption of Mt. St. Helens and estimated transport rates on the Washington shelf by tracing volcanic ash in the bottom sediments.

The wave–current boundary layer models of Smith (1977) and Grant and Madsen (1979) capture the essence of wave–current interaction by predicting stresses and

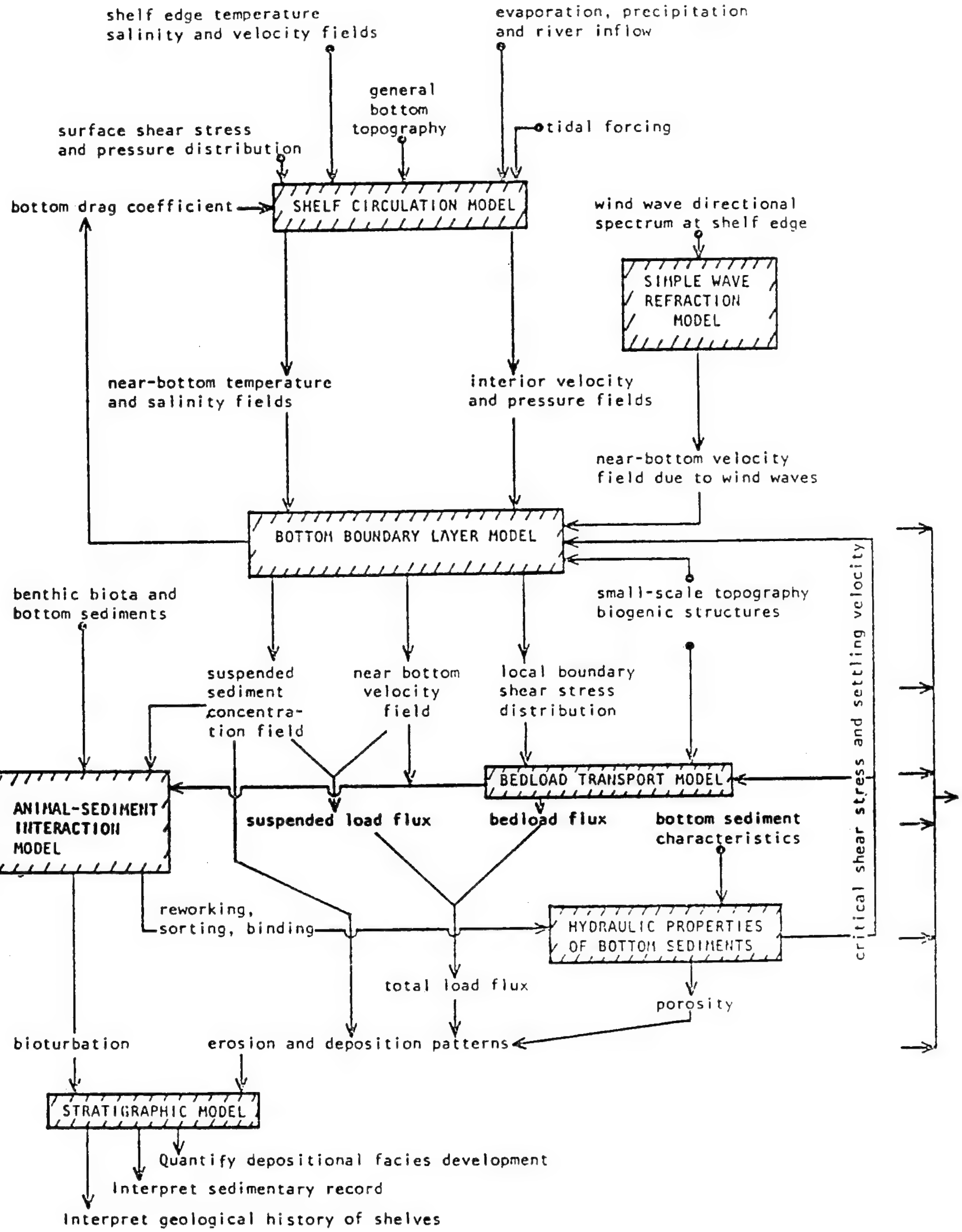


Figure 4: Conceptual model of shelf sedimentation processes developed for the SSDP proposal in 1977.

wave-enhanced bottom roughness. There have been significant advances in integrated sediment-transport models that use combined wave–current solutions. Glenn, Grant, and Madsen developed a one-dimensional (vertical) wave–current boundary-layer model with suspended-sediment stratification and movable bed roughness (Grant and Madsen, 1982; Glenn, 1983; Grant and Madsen, 1986; and Glenn and Grant, 1987). Kachel and Smith (1986, 1989) developed a similar model that also includes a bottom Ekman layer and bottom sediment-size distribution that allows effects of armoring to be investigated. Wiberg *et al.* (1994) have extended the one-dimensional models to include sub-bottom stratigraphy, bioturbation, and optical characterization of suspended sediments (for comparison with OBS and transmissometer data). Other researchers have begun to incorporate elements of the shelf boundary-layer physics in regional transport and deposition models. Recently, Keen and Slingerland (1993a, 1993b) have run a series of models to evaluate hurricane deposits in Gulf of Mexico. The time-dependent models are forced with a wind field and simulate the resulting waves and currents. These are used as input to the Glenn and Grant (1987) wave–current boundary layer model to determine suspended-sediment flux and bottom shear stress, which in turn is used in a sediment-transport model to evaluate stratigraphic changes in the bed. These and other studies indicate that the research community is now able to integrate models of physical and geological processes in order to study the dynamics of sediment movement in the marine environment.

The predictions of the wave–current, moveable-bed bbl models have been compared favorably with field measurements obtained using instrumented bottom tripods (Cacchione and Drake, 1979; Grant *et al.*, 1984; Cacchione and Drake, 1990). In situ bottom tripods measure oceanographic and geological parameters crucial to understanding the relationships between near-bottom flow, bottom stresses, and sediment response at and near the bottom. The latest instrumentation to measure bottom stresses, and suspended-sediment concentration, and particle sizes was successfully deployed during the STRESS experiment conducted on the northern California continental shelf during the winter of 1990–1991. Results from this experiment have significantly improved our understanding of the effects of storms on shelf–sediment resuspension and transport, and have led to important advances in modeling.

Important progress has also been made by relating details of oceanographic processes with the vertical sequences of strata (cores), which provide a time series longer than can be obtained using moored instruments or monitoring programs. The time

scales preserved in stratigraphic records range from seconds to eons, and new techniques allow examination of very fine strata to examine short-duration events. In rapidly accreting muds north of the Amazon River, wave-by-wave records of deposition are preserved in finely laminated strata (e.g., Allison, 1993). The use of new stratigraphic techniques and radioisotope dating allows the ties between water-column processes and the underlying deposits to be examined in areas of active deposition.

While the SSDP conceptual model recognized the importance of animal–sediment interactions, "the study of the effects of organisms on sediment transport is in a particularly uncomfortable state. Although the mechanisms are identifiable conceptually...there is no coherent, verified body of theory for predicting whether, when, or where organism effects will be significant" (Jumars, 1993). This is clearly an avenue of research that could profit from a multidisciplinary approach.

Substantial progress has been accomplished through improved measurement capabilities. A partial list of important new technologies appears below:

Physical Oceanography:

ADCP, cheaper and smarter CTDs, wide range of commercial current meters, drifting devices, LDVs, remote sensing, NDBC buoys

Geological Oceanography:

Suspended sediment:
- Low-cost optical devices
- Acoustic backscatterance suspended-sediment profilers

Particle characteristics:
- Plankton cameras and high-resolution CCD cameras
- Diffractometers
- In-situ flumes
- In-situ settling tubes
- Fluorometer
- Pump samplers

Stratigraphy and bottom characteristics: High-res. sub-bottom profilers
- Acoustic and optical bottom imaging
- Acoustic altimeters
- Seabed density probes
- Special seabed samplers

General:

Smaller and smarter field instruments
  Low power requirements
  Larger memories, more programmability
ROVs, AUVs
Global positioning system

Using these new tools, marine geologists have been addressing the more complex issues involved in sediment transport. Some of these issues are itemized below:

Details of velocity and suspended-sediment profiles

Suspended-sediment stratification and effect on bbl processes

Particle characteristics: size, settling velocity, density

Optical and acoustical response to suspended particles

Mixed-bed response: bed armoring and mixed-bed transport rates

Bottom roughness: physical and hydraulic

Quantification of bioturbation rates

In summary, significant progress has been made on many of the components of the SSDP conceptual model. Basic elements are in place to carry out scientifically meaningful, long-term, integrated studies. The next level of research will incorporate field observations and theory to address increasingly complex issues in shelf sedimentation.

Appendix 7: Reports of Disciplinary Working Groups

A. Coastal Meteorology

Chairman: Richard Rotunno

Rapporteur: Clive Dorman

Participants: Clive Dorman, Richard Rotunno, Jim Overland, Bill Neff

A major organizing goal expressed in the CoOP science prospectus is to determine the relative importance of small-scale and large-scale winds for cross-shelf exchange of water and materials. The working group believes that within the CoOP framework, the major meteorological goal should be to understand the processes that cause meteorological variability over coastal areas.

This meteorological goal touches on most aspects of coastal meteorology over a wide range of scales (Rotunno *et al.*, 1992). The interaction of the coastal ocean and atmosphere, which occurs mainly through the turbulent exchange processes, depends on scales of motion from the synoptic to the smallest turbulence scales. At the synoptic scale, land-falling storms and barrier effects are important (Hobbs *et al.*, 1980; Overland and Walter, 1981; Mass and Ferber, 1990). In mid-latitudes, atmospheric waves may be trapped in the dense marine layer where this layer intersects coastal mountains (Beardsley *et al.*, 1987; Dorman 1985, 1987; Zemba and Friehe, 1987). At the mesoscale, contrasts between the land and sea and variations in the cross-shore and long-shore boundary layer are important, particularly in topographically complex areas. Some broad research areas, where significant contributions to coastal meteorology could be made, follow.

Offshore Variability of the Wind Stress Field Under Different Weather Regimes:

The cross shore variation of wind and wind stress is essentially unknown because of the limited nature of measurements in the coastal zone (Rotunno *et al.*, 1992). Most coastal surface wind measurements are made over land, and most are compromised of local topographic variations. Buoy measurements are rarely made at more than one distance offshore or are of extremely short duration. Ship measurements are too

scattered and far too few to resolve either the diurnal or synoptic meteorological field (hours to a few days).

Wind stress measurements need to resolve variability in the cross shore direction at sites that experience different weather regimes. These could be constructed using bulk methods based upon direct measurements of the winds and temperatures with averages around 0.5 to 1 hour (Fairall and Larsen, 1986; Smith, 1988). The measurements should extend from the coast to beyond the Rossby radius (order of 100–200 km). If made from moored buoys, 4 or 5 in a line perpendicular to the coast should be considered minimal, with the greatest variation expected in the 10 to 50 km next to the coast.

The measurements should be made for a full season or more to insure sufficient number of events upon which to base a statistical analysis. This should be extended to different seasons and different sites, with various degrees of topography.

Coastal Systems Interacting with Surface Terrain:

Storms are complex, three-dimensional systems with a range of scales that extend from the synoptic (several hundred kilometers) to the turbulent (less than a meter). For example, elongated mesoscale bands of intense rainfall within a storm, separated by similar shaped areas of lighter precipitation, are often observed (Hobbs, 1987; Hobbs *et al.*, 1980). These structures depend on the interaction of the cloud micro-physical processes and the large-scale organization of the system. Land-falling storms are even more complex because of the changes in the surface conditions and interactions with topography that feedback to the storm system on many scales (Howells and Kuo, 1988). There are important societal issues because of the damage associated with severe weather.

A particularly interesting case is that of a land-falling storm crossing major meridional topography. The lower level will be partially blocked, causing a major adjustment of the storms internal structure, altering the wind, temperature and pressure fields as well as the clouds and rainfall (Bosart *et al.*, 1973; Forbes *et al.*, 1987). Differential heating between the land and sea could provide additional baroclinic modifications of coastal weather systems.

Coupled Ocean–Atmospheric Responses:

Ocean–atmospheric interactions are of interest because of local intensification of surface wind and weather systems, and the possible importance to climate. While coupling occurs throughout the ocean–atmosphere system, it is especially pronounced in the coastal zone where the ocean and atmosphere have similar temporal and spatial scales. The horizontal variability of the sea surface temperature field and land–sea contrasts lead to the modification of the ocean and atmosphere boundary layers (Elliott and O'Brien, 1977; Mizzi and Pielke, 1984).

Coastal upwelling regions may have especially active coupling (Enriquez and Friehe, 1991. With upwelling, the sea surface and air temperature will decrease, increasing the density and stability of the atmospheric layer. This can result in an increase in the surface wind and changes in the surface wind stress field that enhance upwelling (Nelson, 1977; Kelly, 1985; Davis, 1985a). The interaction between the air and the sea is further complicated in regions of large horizontal surface temperature discontinuities, such as ocean fronts, where rapid changes in the stability and wind stress occur as air flows from one temperature regime to another (Friehe *et al.*, 1991).

Instrument Development:

A number of problems could be tackled using one or more long-range, large payload instrumented aircraft that are capable of providing in-situ atmospheric measurements, obtaining remotely-sensed surface fields, and deploying sensors to the ocean to provide subsurface information along any region of a coast.

Surface based sounding from moored buoys would be useful and should be developed. Radar profilers, laser and acoustical sounders are only adapted to land or ship installations. At present, power consumption is the main limitation of these systems on a buoy.

Satellite measurements of the marine atmosphere do not have the resolution needed for coastal studies. They can, however, provide better coverage of synoptic systems approaching to the coast, i.e., the larger contest with a mesoscale coastal ocean study would occur. In the same way, present atmospheric models do not resolve complex mesoscale variability, such as described above, but may provide a coarse, large-scale

grid, within which three-dimensional atmospheric models can be nested. The methods must ultimately be capable of assimilating remote and in situ data in order to provide quantitative synoptic coverage over extended scales.

B. Physical Oceanography

Chairman: Steve Lentz

Rapporteur: Adriana Huyer

Participants: John Allen, Jack Barth, Mary Batteen, Don Boyer, Ken Brink, Doug Caldwell, Curt Collins, Roland de Szoeke, Richard Dewey, Pat Gallacher, Dale Haidvogel, Barbara Hickey, Mike Kosro, Steve Lentz, Mark Merrifield, Marlene Noble, Jeff Paduan, Terry Paluszkiewicz, Ron Schlitz, Eric Skyllingstad, Ted Strub, Leonard Walstad, Libe Washburn, Xiuahang Zhang

The overwhelming consensus of the physical oceanographers present was that we must greatly increase our understanding of the full three-dimensional circulation processes driven by winds that vary on time-scales of days to seasons to achieve the fundamental CoOP goal of understanding cross-margin transport of physical, chemical, biological and sedimentary materials.

In the decade or so since the previous generation of major west-coast shelf experiments there has been considerable technological progress, providing greatly improved sampling tools, analysis techniques, and modeling approaches. An example is the use of shipborne Acoustic Doppler Current Profilers with GPS navigation and a towed undulating vehicle equipped with a CTD to make rapid, simultaneous, detailed maps of the current and water properties in the upper 300 m. This technique is providing provocative new views of the ocean.

Modeling and continued analysis of data from earlier experiments have also provided a clearer understanding of several important processes, including the wind-driven offshore transport in the ocean surface layer (Smith, 1981; Lentz, 1992) and wind-forced coastal trapped waves along a straight margin (Brink, 1991). Modeling and continued analysis have also highlighted a number of important topics relating to cross-shelf exchange that remain poorly understood. Some of these topics are outlined below. The time is now ripe for a renewed effort to understand fully three-dimensional shelf circulation processes.

Our present knowledge of the wind-driven west coast shelves indicates that the water that upwells over the inner shelf can eventually move 200 km or more offshore (Hood *et al.*, 1990). However, we do not understand how the surface and bottom boundary layers interact over the inner shelf to cause divergence in the Ekman transport, i.e.,

to cause coastal upwelling. Nor do we know the pathways by which water properties, chemical constituents, plankton populations, etc., cross and eventually leave the shelf.

The next generation of problems to be addressed include:

Flow Adjustment to Spatial Variations in Wind and/or Topography:

Our present understanding of shelf-circulation is primarily two-dimensional: most theoretical and numerical models allow for only minor alongshore variations in topography. Similarly, most models do not include small-scale curl or divergence in the wind stress (on scales as small as the shelf-width). There is presently indirect anecdotal evidence that the strong coastal current associated with the upwelling front leaves the shelf and crosses the continental slope offshore of a cape or headland in at least one or two locations along the U.S. west coast. During this transit the water depth increases by more than an order of magnitude. Whether the current maintains its coherent structure during this transit across steep topography is an open question, because no direct observations are available. Similarly coastal winds around headlands may vary greatly on small scales, intensifying to a local wind maximum on the scale of 30 km (Winant *et al.*, 1988). Again, there are few systematic observations available, and the ocean's response to such wind variations is poorly understood.

Cross-Frontal Exchange:

The strong surface gradients and the local maximum in along-front velocity which characterize the coastal upwelling front make it a region of very complex interactions: between wind and water; between waves and currents with differing time scales; among physical, chemical, biological and sedimentary processes; and between different biological populations. The sloping frontal interface may trap internal waves and tides (Hayes and Halpern, 1976), and it may have inherent baroclinic instabilities. Time-varying winds may cause the front to migrate, intensify or decay (Halpern, 1976; Huyer, 1984). Strong cross-frontal shears may cause offshore surface waters to override freshly upwelled waters; frontal convergence may result in subducted populations (Hood *et al.*, 1991). The question of how frontal processes effect cross-shelf exchange is inherently three-dimensional, time-dependent, interdisciplinary, and complex.

Interior Cross-Shelf Circulation:

Previous attempts to identify a simple wind-driven cross-shelf circulation in observations from coastal upwelling regimes (e.g., Mooers *et al.*, 1976) were not fully successful; there is still disagreement whether the cross-shelf upwelling circulation is one-celled or two-celled. Many of the limitations of these earlier studies no longer apply: bottom mounted ADCP's provide current observations with high vertical resolution, and towed vehicles and new sensors now permit us to obtain closely-spaced synoptic data of many different variables over extended periods. On the other hand, we now know that cross-shelf currents have very short correlation scales (Kundu and Allen, 1976; Winant *et al.*, 1987). Consequently, it is unclear whether the concept of one-celled or two-celled circulations is relevant. Nevertheless, physical, biological and chemical observations reveal spatially coherent patterns and suggest there may be systematic subduction of water properties (Washburn *et al.*, 1991). Thus there are two pressing problems: (1) Why are the correlation scales of the cross-shelf currents so short? (2) How do the incoherent cross-shelf currents lead to apparently coherent distributions of particles and water properties?

Inner Shelf Dynamics

The inner shelf is the region where the water depth is sufficiently shallow that the surface and bottom boundary layers directly interact. It is a region of strong cross-shelf gradients in wind stress and offshore (or onshore) transport within the surface Ekman layer. Even in regions with spatially uniform winds, most of the divergence in the cross-shelf Ekman transport is thought to occur over the inner shelf; this is a region where friction is relevant throughout the water column. There have been few observations made over the inner shelf, and so little is known about how the wind-driven shelf circulation adjusts to the coastal boundary condition. Relatively small variations in bathymetry [O(1–10 m)] may also be important in the inner shelf region, where the total water depth is typically less than 50 m. Key questions include: What are the dynamics? How wide is the inner-shelf under various conditions? What is the structure of the three-dimensional turbulence field? Is the inner-shelf circulation two dimensional? Clearly observations are needed to answer these questions and to provide a basis for developing and evaluating models of the inner-shelf circulation.

Bottom-Boundary Layer Dynamics

There are very few measurements of the flow in the bottom-boundary layer in wind-driven shelf regimes (Lentz and Trowbridge, 1991). Consequently, even the most fundamental ideas about the bottom boundary layer, such as the notion of Ekman transport, remain untested. Recent modeling results suggest there are complex consequences of cross-isobath Ekman transport in a stratified fluid over topography (Trowbridge and Lentz, 1991), and observations are needed to test these new hypotheses. Furthermore, because of the lack of observations, the spatial scales of the flow field and bottom stress field are not known. These issues have important consequences to a variety of problems including sediment transport, benthic biology, and the parameterization of bottom stress in shelf models.

Lagrangian Dynamics

We still do most of our thinking and modeling in Eulerian or pseudo-Eulerian terms. Consequently, we do not fully understand the Lagrangian effects of physical processes on modifying the distributions of physical and chemical water properties, plankton populations, and sediment. More work, such as that by Davis (1985b), is needed to fully understand and utilize Lagrangian measurements and, especially, to understand the biological and geological consequences of physical processes.

C. Biological Oceanography

Chairman: Larry Small

Rapporteur: Ian Perry

Participants: Hal Batchelder, Dave Checkley, Larry Clark, Daniel Costa, Tim Cowles, Mary-Lynn Dickson, Percy Donaghay, Mark Eakin, Peter Franks, Steve Gaines, Burt Jones, Steve Lindley, Bruce Menge, Michael Mullin, Sergio Navarrete, Ken Parker, Bill Peterson, Tom Powell, Don Redalje

An overall question that emerged from the discussions of the Biology Working Group concerned the mechanisms by which biological populations are maintained in the wind-driven circulation regimes of the U.S. west coast. Here, "maintained" has the connotation of completion of the life cycle and production of further members of the population. This question has two aspects: (1) growth and death, and (2) transport. Examples of the growth and death aspect must include studies of the local dynamics of phytoplankton production and biomass regulation; for instance, the sources and pathways of nutrient supply for growth, and grazing removal of phytoplankton. Also important in this category are processes which control the species composition of phytoplankton (as an important determinant of food-web dynamics). Similar examples can be posed for zooplankton. Examples of the transport aspect include studies on the control of cross-shelf and alongshore gradients in biomass, primary productivity and phytoplankton species assemblages, and the regulation of horizontal distributions and return/replenishment to "spawning areas." Topographic effects on features of the wind-driven west coast shelf region and their roles in transporting biomass alongshore, and then offshore, were identified as critical problems. Another aspect is control of vertical distributions of phytoplankton and zooplankton through both passive sinking and active vertical migration, and interactions with vertical water circulation. The problem of control of phytoplankton and zooplankton distributional "boundaries," for example at the edges of frontal regions, is thus related to both growth and transport processes.

Two specific problems were discussed by the Biology Working Group, associated with mesoscale processes over the shelf and slope and their linkages towards the shore:

1. "Local" oceanographic influences on nearshore ecosystem dynamics.

Examples were presented of coastal invertebrate communities differing markedly in species composition and recruitment dynamics, despite being near in space (80 km) and with apparently similar habitat characteristics. It was suggested these differences might be due to different upwelling or wave and circulation regimes in the near offshore (e.g., within 10–20 km of shore) although the relevant spatial scales are not well known. Time scales were also recognized as important, since not all wind events drive significant upwelling circulation. More generally, it is not well known what drives the trophic web and ocean productivity within this nearshore region; for example, the relative roles of oceanic versus terrestrial-derived carbon and nutrients, including trace metals, is not known. In turn, the fate of carbon produced nearshore is not well known; for example the proportion transported offshore versus that which settles to the bottom and contributes to local benthic productivity is not well known. This is relevant to the problem of whether benthic populations nearshore are food- or recruitment-limited.

2. Event and shorter time scale processes and their effects on cross-shelf transport.

   Model and observational studies were presented suggesting that short-scale events such as storms and wind reversals may have dramatic effects on upwelling dynamics and the physical circulation regime. One result may be rapid and dramatic cross-shelf transports directed towards shore, which may represent the majority of on-shelf transport in the surface layer during the summer period (when the cross-shelf transport in the surface layer is usually offshore). Potential biological responses to these events include shoreward transport of larvae (producing sporadic recruitment pulses), increased fluxes of material to the benthos (rather than loss of this material offshore) due to cessation of upwelling, high mid-water ammonium concentrations which may support rapid phytoplankton production, and 'trapping' of phytoplankton and zooplankton on the shelf.

   Several problems and considerations were discussed relating to the design of coupled biological–physical–chemical–geological programs. Definition of appropriate time and space scales was considered critical for each problem addressed, both to define the biological program and to enable coupling with the programs in other disciplines. Questions arose as to whether biological problems can be studied in two dimensions, or whether consideration of full three-dimensional fields are necessary. It was agreed that the problems are inherently three-dimensional, requiring consideration of along- and cross-shelf, and vertical directions, as well

as explicit consideration of the appropriate temporal scales. The potential impact of heterogeneity in the alongshelf direction to studies of cross-shelf processes was given as an example. Finally, creative sampling and observational schemes will need to be developed to study these processes on all the relevant time and space scales, and to couple with the other disciplines. The latest technological instrumentation for studies of biological rate processes and distributions must be used (e.g., from satellites to microscale sensors). Program design might include process cruises coupled with moorings and drifters supported by more accessible shore-based monitoring (e.g., monitoring of very near-shore species composition and recruitment events from docks and jetties, etc., but without using ships).

D. Chemical Oceanography

Chairman: Ken Bruland

Rapporteur: Ken Johnson

Participants: Ken Johnson, Ken Bruland, Fred Prahl, Roland Wollast

The chemical oceanographers, meeting as a discipline, focused on two classes of problems that require integrated chemical, physical, geological and biological studies. These are (1) the chemical processes that regulate the structure of the upper ocean community, and (2) the processes that transform the composition of sediments as they move across the continental margin. Both classes of problems have become much more tractable because of advances in instrumental capabilities.

Recent advances in the instrumental capabilities available to chemical oceanographers have led to a remarkable advance in our understanding of chemical and biological interactions in the ocean. It is now generally accepted that, in the pelagic regions of the ocean, the structure of the ecosystem is controlled by availability of trace nutrients such as iron that act in concert with the availability of nitrogen nutrients to control the size structure of phytoplankton populations. The phytoplankton size structure, in turn, controls the nature of the grazer population and fishery yield of the population. Tests of this paradigm in the equatorial Pacific are a major component of the Joint Global Ocean Flux Study (JGOFS) program.

However, the implications of this model in coastal systems have generally been ignored. It is often assumed that coastal systems are replete with required trace nutrients such as iron and that nitrogen availability controls population dynamics. Careful consideration of the very limited amount of available data for metals in the coastal zone suggests that this is not so. The characteristic scale lengths for iron transport are very short, and must be extremely variable, due to the very particle reactive nature of iron. The interaction of iron reactivity and physical transport processes would produce a very non-linear impact on ecosystem structure. Observations of nitrate and chlorophyll in Eastern Boundary systems demonstrates that there are, in fact, large non-linearities in the relationship of these properties (Small and Menzies, 1981; Chavez *et al.*, 1991). This is indirect evidence that the ecosystem is influenced by processes other than nitrate availability. A testable hypothesis is that trace-nutrient availability is the process that acts to control the non-linearity in nitrate–chlorophyll relationships.

It is now possible to analyze many of the bio-regulating trace metals (iron, manganese, cobalt, zinc) routinely on board ship due to advances in automated analysis of these chemicals. These methods could be used to gain much greater insight in the interaction of physical, biological and chemical processes in the coastal ocean. Figure 5 shows many of the important processes that act at the ocean margin to control ecosystem structure. The important classes of chemical processes that need to be considered are:

biological–dissolved chemical interactions
near bottom processes
advective transport (geostrophic and Ekman).

We need to quantify the significance of the various transport pathways and reaction mechanisms. It was suggested that a non-river influenced margin would make this work easier to interpret.

The trace organic composition of particles along river-dominated margins shows a distinct change as one moves offshore. Isotopic and trace chemical analyses demonstrate that this change is not simply a result of dilution of the terrestrial material by particles of a marine origin. This change must be due to the composition of terrestrial material, transport of particles in the bed and suspended loads, and fractionation during deposition. An integrated study of this problem would allow the remineralization rates of riverine organic carbon to be determined, which would quantify an important component of the global carbon cycle.

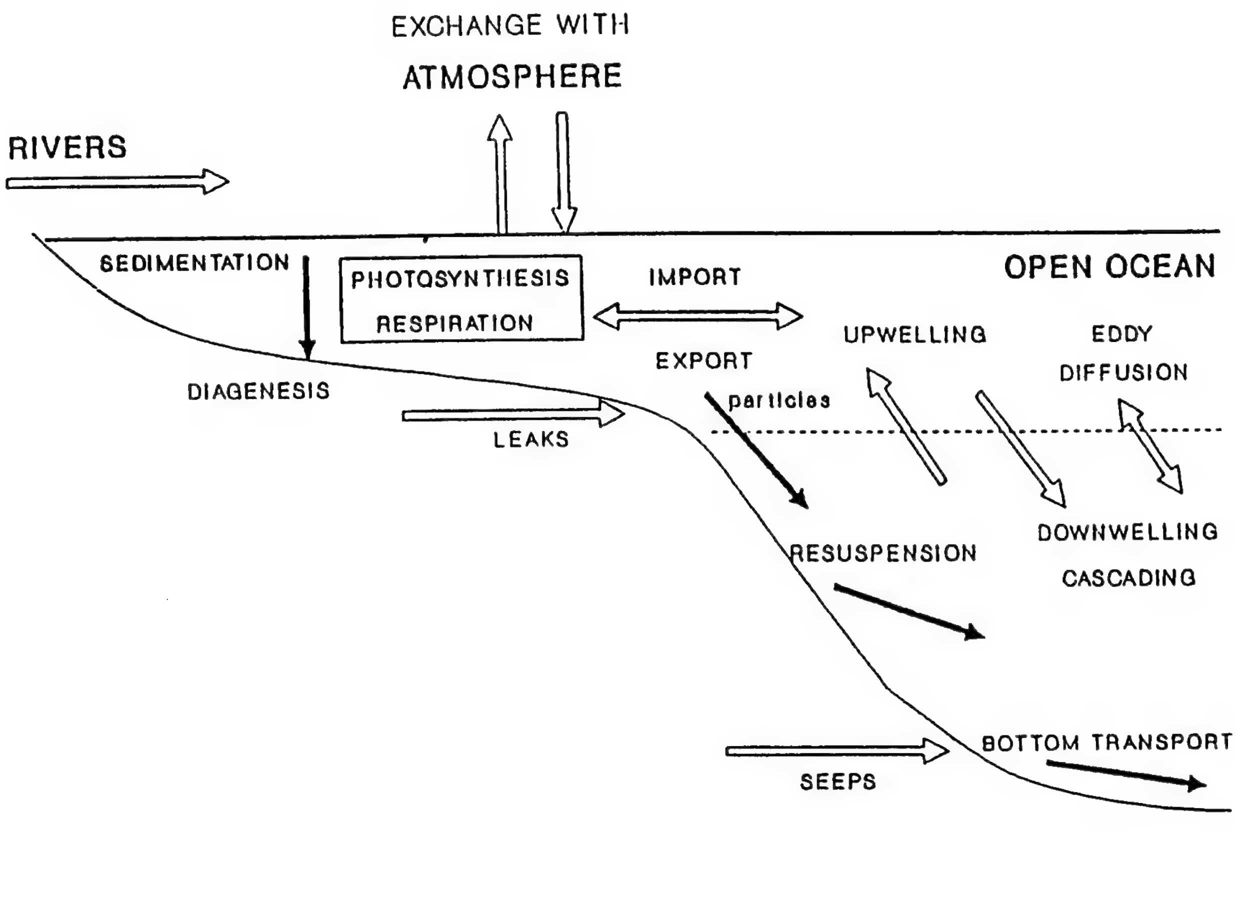


Figure 5: Circulation and fluxes at ocean margins.

E. Geological Oceanography

Chairman: Dick Sternberg

Rapporteur: Chris Sherwood

Participants: Dave Cacchione, Dave Drake, Chuck Nittrouer, Chris Sherwood, Dick Sternberg

For a variety of reasons, inorganic particulate matter introduced into continental-margin areas represents one of the major components associated with cross-margin transport. Terrestrial particulate matter, although introduced through river plumes, mostly settles rapidly to the seabed and is transported by benthic boundary layer (bbl) processes. Fine inorganic particulate matter (e.g., silt and clay particles) is important in scavenging many particle reactive chemical species (e.g., radionuclides, organic matter, pesticide residues, etc). It is co-deposited with various forms of terrestrial carbon and marine derived organic particles, and represents major sites of nutrient regeneration. For these reasons, formation, maintenance, and dynamic fluctuations of sedimentary deposits on continental margins have an important bearing on, and are important indicators of, the cross-margin transport of many substances.

1. Sedimentary deposits on continental margins are dynamic features (not static deposits) and represent the interplay between physical processes and sediment characteristics to produce regions where certain classes of sediments can be deposited. Boundaries of these deposits change over time and the surface sediments fluctuate in response to short-term deposition and erosion events. We need to know:

    (a) How do physical processes constrain the boundaries of shelf sedimentary deposits (e.g., cross-margin gradients in bottom stress? What linkages between bbl forcing (e.g., waves, currents, frontal dynamics) and sediment characteristics produce the observed deposits on any margin?

    (b) How to model, using appropriate forcing mechanisms, sediment erosion, deposition, and flux of particulates to produce and maintain identifiable sedimentary deposits. Development of modeling capabilities requires comprehensive knowledge of:

        i. microtopography,

ii. benthic-organism effects with respect to sediment mixing, and seabed roughness patterns which feedback to boundary flow conditions and threshold of grain motion,

iii. sedimentary characteristics,

iv. surficial seabed stratigraphy.

2. Sedimentary deposits on continental margins record some of the sedimentary history of the past 10,000 years. Stratigraphic relationships comprising these deposits are an important link to:

   (a) determining depositional history during the Holocene sea-level transgression and the modern high stand;

   (b) understanding processes of strata development under modern shelf processes (strong sedimentation events);

   (c) determining post-depositional changes in strata and chemical/particulate transformations as a results of chemical and biological activity;

   (d) interpreting the time-history of climate variability over hundreds of years to millennia; and

   (e) relating stratal signatures recorded in recent margin sedimentary deposits to the geological record that, on the west coast of the United States (an active tectonic margin), is exposed in uplifted deposits along the coast.

3. Inorganic particulates in the silt- and clay-size range are known to scavenge a variety of important chemical species and undergo a range of transformations from the time they are introduced in river plumes until they are deposited in margin deposits. Thus the formation, maintenance, and fluctuations of margin deposits may have a major, if not dominant, influence on most aspects of the continental margin environment (e.g., benthic populations, burial of organic matter, source of nutrients, storage of resting cells and spores, sinking cells, and larvae, etc).

   (a) Processes of hydraulic sorting not only affect inorganic particulates but are also evident in the distribution of particulate terrestrial carbon (and associated organic components). Thus inorganic sediments are often co-deposited with these other materials (i.e., where you find sediments you also find terrestrial carbon and other organic materials);

(b) During upwelling events that happen to coincide with periods of major river discharge, particulates settling through river plumes can scavenge marine-derived chemical species and incorporate them into bottom deposits;

(c) During downwelling events, also often times of major river discharge, sediment-laden river discharge is confined to a region of the middle and inner shelf. Downwelling events also represent times of major storms when active resuspension and redistribution of bottom sediments occurs and possibly important fronts may form on the midshelf region. Thus the ultimate form and locations of sedimentary deposits may originate during downwelling conditions.

(d) The physical and biological processes associated with shelf deposition greatly influence chemical processes in bottom sediments, affecting nutrient cycling, chemical transformation, and early diagenesis.

Appendix 8: Meeting Announcement

The interdisciplinary workshop 'WIND-DRIVEN TRANSPORT PROCESSES ON THE U.S. WEST COAST SHELF' was the first CoOP process study workshop. An open invitation to all interested scientists was widely distributed through bulk mailing and posting to OMNET bulletin boards. The announcement read:

An interdisciplinary CoOP (Coastal Ocean Processes) science workshop to be held in Portland, Oregon, 14 through 16 July 1993.

The CoOP Scientific Steering Committee has recommended that major CoOP process studies be developed through substantial input from the scientific community. Each process study will be initiated by a community workshop that will formulate key scientific questions and fruitful approaches toward the study of transport processes on the coastal margin. The first workshop in the series will be on "wind-driven transport processes." Subsequent workshops will occur as CoOP develops and as resources for process studies become available.

The CoOP Science Prospectus (Brink *et al.*, 1992) states that a high priority for CoOP research is "to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins." Therefore, the goal of the "wind-driven transport" workshop is to create a document that will define an interdisciplinary (biological, chemical, geological and physical oceanography, and marine meteorology) CoOP process study. The study should focus on cross-shelf transport phenomena centering on the predominantly wind-driven currents of the United States west coast continental margin. There appears to be a mutually beneficial opportunity to conduct a CoOP process study off the west coast of the United States in cooperation with GLOBEC (Global Ocean Ecosystem Dynamics), perhaps as early as 1996. Although close cooperation with GLOBEC is anticipated, CoOP must generate its own science plan that satisfies its own broad mandate in the coastal ocean. The planned cross-margin transport study must be fully interdisciplinary, and could include intensive field work lasting up to two years.

The workshop report must address the following topics:

- What are the important scientific problems to be addressed in the study, and why are they important?
- How should these problems be addressed in a cohesive, interdisciplinary manner? Answering this question would entail substantial ideas about modeling and field work as well as choices about the location for such a study.

The quality of the report produced by the workshop will be critical for the success of any resulting CoOP process study.

All interested scientists are welcome to attend the meeting and contribute to the report. Statements of intention to attend and logistical questions should be directed to Mary Ann Lucas (WHOI: 508 548-1400, ext. 2506, or internet: mlucas@whoi.edu) by June 10. Blocks of hotel rooms have been reserved, and reservations should be made by June 14; information will be provided when intention to attend is expressed. Queries about the meeting content should be directed to Robert L. Smith, Oregon State University, who chairs the organizing committee (Phone 503 737-2926; FAX:503 737-2064; Internet e-mail: rsmith@oce.orst.edu).

Organizing committee (and discipline): Robert L. Smith, OSU (physical), Ken Bruland, UCSC (chemical), David Rogers, UCSD (meteorological), Larry Small, OSU (biological), Richard Sternberg, UW (geological)

Reference: Brink, K. H. *et al.*, 1992: Coastal Ocean Processes: A Science Prospectus. Woods Hole Oceanographic Institution Tech Rept WHOI-92-18, 103pp. (available from K. H. Brink).

Appendix 9: Agenda

Coastal Ocean Processes Workshop

Wind-Driven Transport Processes on the U.S. West Coast

July 14–16, 1993

Portland State University, Portland, Oregon

Wednesday, July 14

Morning: Plenary Meeting — Smith Memorial, Rooms 290 & 292

0830–0900	Registration
0900–0930	Welcoming and Tasking (R. Smith)
0930–1430	The important relevant problems as seen from the disciplinary perspectives with half-hour talks (each followed by 10 minutes for questions).
0930–1010	Coastal Meteorology (Richard Rotunno, NCAR)
1010–1030	*Coffee Break*
1030–1110	Physical Oceanography (Steve Lentz, WHOI)
1110–1150	Biological Oceanography (Larry Small, OSU)
1200	*Lunch*
1300–1340	Chemical Oceanography (Ken Bruland, UCSC)
1340–1420	Geological Oceanography (Dick Sternberg, U.Washington)
1420–1430	SERMON (R. Smith)
1430–1450	*Break*
1450–1600	Five disciplines meet separately to refine or formulate the important relevant problems, with the CoOP interest in cross-shelf transport processes in focus and the CoOP interdisciplinary imperative in mind.
1600–1630	Plenary: 5-minute summary of discussions from each of the working groups.
1630–1700	Open Discussion (moderated by K. Brink)

***** The organizing committee, speakers, and the chairs of the working groups meet Wednesday evening to distill questions and make Interdisciplinary Working Group assignments for the following day. *****

Thursday, July 15

0830–0900 Plenary: Talk on components of the U.S. GLOBEC West Coast study (T. Strub).

0900–0930 Talk on OMEX (European Community Ocean Margin Exchange Project) by Professor Roland Wollast.

0930–0945 Charges to new Interdisciplinary Working Groups, which must:

1. Refine question (identify missed questions; discard some?)
2. Provide a framework for answering questions.
   - How should the scientific problems be addressed in a cohesive, interdisciplinary manner?
     Answering this will entail substantial ideas about modeling and field work as well as choices about the location for such a study.

0945–1015 *Break*

1015–1200 Interdisciplinary Working Group discussions.

1200–1330 *Lunch* *** Interdisciplinary Working Group chairs meet with organizing committee.

1330–1500 Working Group discussions continue (and begin writing!)

1500–1530 *Break*

1530–1730 Plenary: Reports from the Interdisciplinary Working Groups and discussion.

Friday, July 16

0830–0900 Plenary: Expectations and Reminders (relations of questions to overall CoOP goal, consideration of a potential joint study of GLOBEC).

0900–1200 Working Group discussions continue.

1200–1330 *Lunch*

1330–1500 Final considerations in Interdisciplinary Working Groups and report writing.

1500–1530 *Break*

1530–1700 Plenary: Final reports from the Interdisciplinary Working Groups and discussion from the floor.

Appendix 10: List of Attendees

Mark Abbott
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-4045
FAX:
Internet: mark@oce.orst.edu
OMNET:
Discipline: Biological Oceanography

John Allen
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-2928
FAX: (503) 737-2064
Internet:
OMNET: Oregon.State
Discipline: Physical Oceanography

Jack Barth
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-1607
FAX: (503) 737-2064
Internet: barth@oce.orst.edu
OMNET: Oregon.State
Discipline: Physical Oceanography

Hal Batchelder
Division of Environmental Studies
University of California, Davis
Davis, CA 95616-8576
PHONE: (916) 752-2332
FAX: (916) 752-3350
Internet: hpbatchelder@ucdavis.edu
OMNET: H.Batchelder
Discipline: Biological Oceanography

Mary Batteen
Code OC/BV
Dept. of Oceanography
Naval Postgraduate School
Monterey, CA 93943-5000
PHONE: (408) 656-3265
FAX: (408) 656-2712
Internet: batteen@oc.nps.navy.mil
OMNET: Ocean.NPS
Discipline: Physical Oceanography

Donald Boyer
Dept. Mechanical & Aerospace Eng.
Arizona State University
Tempe, AZ 85287-6106
PHONE: (602) 965-1382
FAX: (602) 965-1384
Internet:
OMNET: D.Boyer
Discipline: Physical Oceanography

Kenneth Brink
Physical Oceanography Dept.
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
PHONE: (508) 457-2000, ext. 2535
FAX: (508) 457-2181
Internet:
OMNET: K.Brink
Discipline: Physical Oceanography

Kenneth Bruland
Center for Coastal Marine Studies
Division of Natural Sciences
University of California
Santa Cruz, CA 95060
PHONE: (408) 459-4587
FAX:
Internet: Bruland@cats.ucsc.edu
OMNET: K.Bruland
Discipline: Chemical Oceanography

David Cacchione
U.S. Geological Survey, MS-999
345 Middlefield Road
Menlo Park, CA 94025
PHONE: (415) 354-3089
FAX: (415) 354-3191
Internet: davec@octopus.wr.usgs.gov
OMNET: D.Cacchione
Discipline: Geology

Douglas Caldwell
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-5192
FAX: (503) 737-2064
Internet: caldweld@oce.orst.edu
OMNET: Oregon. State
Discipline: Physical Oceanography

David Checkley
Mail Code A-018
Scripps Institution of Oceanography
La Jolla, CA 92093-0218
PHONE: (619) 534-4228
FAX: (619) 534-6500
Internet: dcheckley@ucsd.edu
OMNET: D.Checkley
Discipline: Biological Oceanography

Larry Clark
Oceanographic Facilities Support Sec.
National Science Foundation
1800 G Street, NW
Washington, DC 20550
PHONE: (202) 357-7837
FAX: (202) 357-7621
Internet: hclark@nsf.gov
OMNET: L.Clark.NSF
Discipline:

Curtis Collins
Dept. of Oceanography
Naval Postgraduate School
Monterey, CA 93943
PHONE:
FAX:
Internet: collins@wake.oc.nps.navy.mil
OMNET: C.Collins.NPS
Discipline: Physical Oceanography

Dan Costa
ONR Code 3411
Ballston Tower One
800 No. Quincy Street
Arlington, VA 22217-5660
PHONE: (703) 696-2085
FAX: (703) 696-1212
Internet: costa@cod.nosc.mil
OMNET: D.Costa
Discipline: Biological Oceanography

Tim Cowles
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3566
FAX: (503) 737-2064
Internet: cowles@oce.orst.edu
OMNET: T.Cowles
Discipline: Biological Oceanography

Roland de Szoeke
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3160
FAX: (503) 737-2064
Internet: szoeke@oce.orst.edu
OMNET: R.Deszoeke
Discipline: Physical Oceanography

Richard Dewey
Science Applications International Corp.
13400 Northup Way, Suite B-36
Bellevue, WA 98005
PHONE: (206) 747-7152
FAX: (206) 747-9211
Internet: DEWEY@swvb.nw.saic.com
OMNET: R.Dewey
Discipline: Physical Oceanography

Mary-Lynn Dickson
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02879
PHONE: (401) 792-0329
FAX:
Internet: dickson@micmac.gso.uri.edu
OMNET:
Discipline: Biological Oceanography

Scott Dinnel
Center for Marine Science
University of Southern Mississippi
Stennis Space Center, MS 39529
PHONE: (601) 688-3401
FAX: (601) 688-1121
Internet: sdinnel@whale.st.usm.edu
OMNET:
Discipline: Physical Oceanography

Percy Donaghay
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882-1197
PHONE: (401) 792-6944
FAX: (401) 792-6160
Internet:
OMNET: P.Donaghay
Discipline: Biological Oceanography

Clive Dorman
San Diego State University
Dept. of Geological Sciences
San Diego, CA 92182
PHONE: (619) 594-5707
FAX:
Internet: clive@coast.ucsd.edu
OMNET:
Discipline: Coastal Meteorology

David Drake
U.S. Geological Survey, MS-999
345 Middlefield Road
Menlo Park, CA 94025
PHONE:
FAX: (415) 354-3191
Internet: drake@octopus.wr.usgs.gov
OMNET:
Discipline: Geology

C. Mark Eakin
NOAA, Office of Global Programs
1100 Wayne Ave., Suite 1225
Silver Spring, MD 20910
PHONE: (301) 427-2089, Ext. 710
FAX: (301) 427-2073
Internet: Mark=Eakin
%GP%NOAA@Vines.erl.gov
OMNET: M.Eakin
Discipline: Coral Reef Ecology

Lee Eddington
Code P3542
Geophysics Department
Naval Air Warfare Center
Point Mugu, CA 93042-5000
PHONE: (805) 525-8090
FAX: (805) 525-4817
Internet:
OMNET: L.Eddington
Discipline: Meteorology

Peter Franks
Mail Code A-018
Scripps Institution of Oceanography
La Jolla, CA 92093-0218
PHONE: (619) 534-7528
FAX: (619) 534-6500
Internet: franks@ucsd.edu
OMNET: P.Franks
Discipline: Biological Oceanography

Steven Gaines
Dept. of Biology & Medicine
Box G-W
Brown University
Providence, RI 02912
PHONE: (401) 863-3936
FAX: (401) 863-2166
Internet: steven_gaines@brown.edu
OMNET:
Discipline: Marine Ecology

Patrick Gallacher
Code 7331
NRL-SSC
Stennis Space Center, MS 39529-5004
PHONE: (601) 688-5315
FAX: (601) 688-4759
Internet: gallachr@mthood.nrlssc.navy.mil
OMNET: P.Gallacher
Discipline: Physical Oceanography

Dale Haidvogel
Inst. of Marine & Coastal Resources
P.O. Box 231, Blake Hall
Rutgers University
New Brunswick, NJ 08903-0231
PHONE: (908) 932-6555, ext. 256
FAX: (908) 932-8578
Internet: dale@ahab.rutgers.edu
OMNET:
Discipline: Physical Oceanography

Barbara Hickey
School of Oceanography, WB-10
University of Washington
Seattle, WA 98022
PHONE: (206) 543-4737
FAX: (206) 68503354
Internet: bhickey@uwashington.edu
OMNET: B.Hickey
Discipline: Physical Oceanography

Adriana (Jane) Huyer
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-2108
FAX: (503) 737-2064
Internet: huyer@oce.orst.edu
OMNET: A.Huyer
Discipline: Physical Oceanography

Kenneth Johnson
Moss Landing Marine Labs
Box 450
Moss Landing, CA 95039
PHONE: (408) 755-8657
FAX: (408) 753-2826
Internet: johnson@mlml.calstate.edu
OMNET: K.Johnson
Discipline: Chemistry

Burton Jones
Dept. of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0731
PHONE: (213) 740-5765
FAX: (213) 740-8801
Internet: burton@oceana.usc.edu
OMNET: B.Jones
Discipline: Biological Oceanography

Michael Kosro
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3079
FAX: (503) 737-2064
Internet: kosro@OQ.orst.edu
OMNET: M.Kosro
Discipline: Physical Oceanography

Steven Lentz
Dept. of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02534
PHONE: (508) 457-2000, ext. 2808
FAX: (508) 457-2181
Internet: slentz@aqua.whoi.edu
OMNET: S.Lentz
Discipline: Physical Oceanography

Steve Lindley
Duke University Marine Laboratory
Pivers Island
Beaufort, NC 28516
PHONE: (919) 728-2111
FAX:
Internet: slindley@acpub.duke.edu
OMNET: R.Barber
Discipline: Biological Oceanography

Paul Martin
National Research Laboratory
Code 7331 Bulding 1103
Stennis Space Center, MS 39529
PHONE: (601) 688-5447
FAX:
Internet: martin@blackfin.nrlssc.navy.mil
OMNET:
Discipline: Physical Oceanography

Julie McClean
Dept. of Oceanography
Naval Postgraduate School
Monterey, CA 93943-5100
PHONE: (408) 656-2437
FAX: (408) 656-2712
Internet: mcclean@oc.nps.navy.mil
OMNET: Ocean.NPS
Discipline: Physical Oceanography

Bruce Menge
Dept. of Zoology
Oregon State University
Corvallis, OR 97331-2914
PHONE: (503) 737-5358
FAX: (503) 737-0501
Internet: menge@bcc.orst.edu
OMNET:
Discipline: Marine Ecology

Mark Merrifield
MPL Mail Code A-013
Scripps Institution of Oceanography
La Jolla, CA 92093-0213
PHONE: (619) 534-2384
FAX:
Internet: markm@cassis.ucsd.edu
OMNET:
Discipline: Physical Oceanography

Mike Mullin
Marine Life Research Group
Mail Code A-018
Scripps Institution of Oceanography
La Jolla, CA 92093-0218
PHONE: (619) 53402711
FAX: (609) 534-6500
Internet: mmullin@coast.ucsd.edu
OMNET:
Discipline: Biological Oceanography

Sergio Navarrete
Dept. of Zoology
Oregon State University
Corvallis, OR 97330-2194
PHONE: (503) 737-5359
FAX: (503) 737-0501
Internet: navarres@bcc.orst.edu
OMNET:
Discipline: Benthic Marine Ecology

William Neff
ERL R/E/WP7
325 Broadway
Boulder, CO 80304
PHONE: (303) 497-6265
FAX: (303) 497-6978
Internet:
OMNET: W.Neff
Discipline: Atmospheric Science

Charles Nittrouer
Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-5000
PHONE: (516) 632-8652
FAX: (516) 632-8820
Internet: cnittrou@ccmail.suny.sb.edu
OMNET: C.Nittrouer
Discipline: Geological Oceanography

Marlene Noble
U.S.G.S
345 Middlefield Road MS999
Menlo Park, CA 94025
PHONE: (415) 354-3100
FAX:
Internet: marlene@octopus.wr.usgs.gov
OMNET: M.Noble
Discipline: Physical Oceanography

James Overland
PMEL/NOAA
7600 Sand Point Way NE
Seattle, WA 98115
PHONE: (206) 526-6795
FAX: (206) 526-6485
Internet: overland@noaapmel.gov
OMNET: J.Overland
Discipline: Meteorology

Jeffrey Paduan
Code OC/Pd
Naval Postgraduate School
Monterey, CA 93943
PHONE: (408) 656-3350
FAX: (408) 656-2712
Internet: paduan@oc.nps.navy.mil
OMNET: Ocean.NPS
Discipline: Physical Oceanography

Terri Paluszkiewicz
Pacific Northwest Lab
1529 West Sequim Bay Road
Sequim, WA 98382
PHONE: (206) 681-3615
FAX: (206) 681-4115
Internet: tp@circe.pnl.gov
OMNET: T.Paluszkiewicz
Discipline: Physical Oceanography

Kenneth Parker
NOAA Pacific Marine Environment Lab
7600 Sand Point Way NE, Bldg. 3
Seattle, WA 98115-0070
PHONE: (206) 526-6215
FAX: (206) 526-6485
Internet: kparker@pmel.noaa.gov
OMNET: K.Parker.PMEL
Discipline: Biological Oceanography

Ian Perry
Pacific Biological Station
Dept. of Fisheries and Oceans
Nanaimo, B.C., CANADA V9R 5K6
PHONE: (604) 756-7137
FAX: (604) 756-7053
Internet: perryI@pbs.pbs.dfo.ca
OMNET: PBS.NANAIMO
Discipline: Biology/Fisheries Oceanog.

Bill Peterson
NOAA NMFS F/RE3
1335 East West Highway
Silver Spring, MD 21801
PHONE: (301) 713-2367
FAX: (301) 588-4853
Internet:
OMNET: W.Peterson
Discipline: Biological Oceanography

Thomas Powell
Division of Environmental Studies
University of California
Davis, CA 95616-8576
PHONE: (916) 752-4163 or 1180
FAX: (916) 752-3350
Internet: tmpowell@ucdavis.edu
OMNET: T.Powell
Discipline: Physical/Biological Oceanog.

Fred Prahl
College of Oceanic & Atmos. Sciences
Dept. of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3969
FAX: (503) 737-2064
Internet: fprahl@oce.orst.edu
OMNET:
Discipline: Chemical Oceanography

Donald Redalje
USM Center for Marine Science
Building 1103
Stennis Space Center, MS 39529
PHONE: (601) 688-1174
FAX: (601) 688-1121
Internet: dredalje@whale.st.usm.edu
OMNET: D.Redalje
Discipline: Biological Oceanography

Richard Rotunno
N.C.A.R.
P.O. Box 3000
Boulder, CO 80307-3000
PHONE: (303) 497-8904
FAX: (303) 497-8181
Internet: rotunno@ncar.ucar.edu
OMNET:
Discipline: Coastal Meteorology

Ronald Schlitz
ONR Code 321CS
Office of Naval Research
Ballston Towers One
800 North Quincy Street
Arlington, VA 22217-5660
PHONE: (703) 696-4591
FAX: (703) 696-3945
Internet:
OMNET: R.Schlitz
Discipline: Physical Oceanography

Christopher Sherwood
Battelle Marine Science Lab.
1529 West Sequim Bay Road
Sequim, WA 98382
PHONE: (206) 681-3618
FAX: (206) 681-3699
Internet: crs@constance.pnl.gov
OMNET:
Discipline: Geology

Eric Skyllingstad
Pacific Northwest Laboratory
1524 West Sequim Bay Road
Sequim, WA 98382
PHONE: (206) 681-3617
FAX: (206) 681-3699
Internet: eds@windfall.pnl.gov
OMNET:
Discipline: Physical Oceanography

Larry Small
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3960
FAX:
Internet:
OMNET: Oregon.State
Discipline: Biological Oceanography

Robert Smith
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-2926
FAX: (503) 737-2064
Internet: rsmith@oce.orst.edu
OMNET:
Discipline: Physical Oceanography

Richard Sternberg
School of Oceanography, WB-10
University of Washington
Seattle, WA 98195
PHONE: (206) 543-0589
FAX: (206) 685-3354
Internet: rws@ocean.washington.edu
OMNET: R.Sternberg
Discipline: Geological Oceanography

Ted Strub
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-3015
FAX: (503) 737-2064
Internet: pts@osuvax.oce.orst.edu
OMNET: T.Strub
Discipline: Physical Oceanography

Philip Taylor
Division of Ocean Sciences
National Science Foundation
1800 G Street, NW
Washington, DC 20550
PHONE: (202) 357-9600
FAX: (202) 357-7621
Internet: prtaylor@nsf.gov
OMNET: P.Taylor.PHIL
Discipline: Biological Oceanography

Leonard Walstad
College Oceanic/Atmospheric Sciences
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-2070
FAX: (503) 737-2064
Internet: lwalstad@oce.orst.edu
OMNET: L.Walstad
Discipline: Physical Oceanography

Libe Washburn
Dept. of Geography
University of California
Santa Barbara, CA 93106-4060
PHONE: (805) 893-7045 or 8480
FAX: (805) 893-2578
Internet: washburn@geog.ucsb.edu
OMNET: L.Washburn
Discipline: Physical Oceanography

Richard Wiener
College of Oceanography
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
PHONE: (503) 737-2368
FAX: (503) 737-2064
Internet: rwiener@oce.orst.edu
OMNET:
Discipline: Physical Oceanography

Roland Wollast
Laboratoire de Oceanographie
Universite Libre de Bruxelles
Campus de la Plaine - CP 208
1050 Bruxelles, BELGIUM
PHONE:
FAX: 32-2-6463492
Internet:
OMNET:
Discipline: Chemical Oceanography

Catherine Woody
NOAA NDBC W/DB4
Bldg. 1100
Stennis Space Center, MS 39520
PHONE: (601) 688-1021
FAX: (601) 688-3153
Internet:
OMNET: NDBC.Center
Discipline: Physical Oceanography

Xiuzhang Zhang
Dept. Mechanical & Aerospace Eng.
Arizona State University
Tempe, AZ 85287-6106
PHONE: (602) 965-2742
FAX: (602) 965-1384
Internet: ATXXZ@ASUACAD.Bitnet
OMNET:
Discipline: Physical Oceanography

DOCUMENT LIBRARY

Distribution List for Technical Report Exchange – May 5, 1994

University of California, San Diego
SIO Library 0175C (TRC)
9500 Gilman Drive
La Jolla, CA 92093-0175

Hancock Library of Biology & Oceanography
Alan Hancock Laboratory
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts & Exchanges
Library
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, NS, B2Y 4A2, CANADA

Commander
International Ice Patrol
1082 Shennecossett Road
Groton, CT 06340-6095

NOAA/EDIS Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Library
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah, GA 31411

Institute of Geophysics
University of Hawaii
Library Room 252
2525 Correa Road
Honolulu, HI 96822

Marine Resources Information Center
Building E38-320
MIT
Cambridge, MA 02139

Library
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Science Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
University of Washington
Seattle, WA 98195

Library
R.S.M.A.S.
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149

Maury Oceanographic Library
Naval Oceanographic Office
Building 1003 South
1002 Balch Blvd.
Stennis Space Center, MS 39522-5001

Library
Institute of Ocean Sciences
P.O. Box 6000
Sidney, B.C. V8L 4B2
CANADA

Library
Institute of Oceanographic Sciences
Deacon Laboratory
Wormley, Godalming
Surrey GU8 5UB
UNITED KINGDOM

The Librarian
CSIRO Marine Laboratories
G.P.O. Box 1538
Hobart, Tasmania
AUSTRALIA 7001

Library
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside L43 7 RA
UNITED KINGDOM

IFREMER
Centre de Brest
Service Documentation - Publications
BP 70 29280 PLOUZANE
FRANCE

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-94-20	2.	3. Recipient's Accession No.
4. Title and Subtitle Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast			5. Report Date September 1994
			6.
7. Author(s) R.L. Smith and K.H. Brink			8. Performing Organization Rept. No. WHOI-94-20
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) OCE-92-24824 (G)
12. Sponsoring Organization Name and Address National Science Foundation			13. Type of Report & Period Covered Technical Report
			14.

15. Supplementary Notes

This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-94-20.

16. Abstract (Limit: 200 words)

Wind-driven transport occurs on nearly all of the world's continental shelves. A workshop, open to all interested scientists, was held in Portland, Oregon, on July 14–16, 1993, to assess the need for a major interdisciplinary study, and to begin defining the relevant questions and approaches. Specific questions were posed in the areas of air-sea feedback, sources and sinks of chemicals in the euphotic zone, plankton distributions and benthic exchanges. The consensus of the entire workshop was that a CoOP study of wind-driven transport processes should be made and should take place over the continental margin adjacent to the U.S. west coast. The central question to be addressed is: What processes control the cross-margin transport of biological, chemical and geological materials in a strongly wind-driven system? Some recommendations were made for locations and measurement techniques to be used in the envisioned two-year field program.

17. Document Analysis a. Descriptors

coastal ocean
wind-driven
upwelling

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Approved for public release; distribution unlimited.	UNCLASSIFIED	140
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18) *See Instructions on Reverse* **OPTIONAL FORM 272 (4-77)** (Formerly NTIS-35) Department of Commerce